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EVALUATION OF AUXILIARY AGENTS AND SYSTEMS FOR AIRCRAFT GROUND FIRE SUPPRESSION. PHASE I

Sami Atallah, et al

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This phase was devoted to the definition of auxiliary agent/system requirements and to the review of existing knowledge on the performance of various agents and systems under particular fire and environmental conditions likely to be encountered at military airports. Where knowledge was lacking, a series of environmental and small scale fire tests were conducted, the latter on three mockups simulating fires in an aircraft engine, fuel running along the incline of an aircraft wing and in a ruptured fuel tank containing reticulated foam.

Candidate auxiliary agents and systems were recommended for the various requirements identified. A test program aimed at reducing the number of agents and systems to a minimum was planned and proposed for conduct in the second phase of the project. Two other areas were identified as requiring additional work and recommended for the second phase. These were the development of a more effective magnesium fire extinguishing agent and system and the optimization of the design of nozzles and delivery mechanisms used on portable and wheeled extinguishers.

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FOREWORD

This report describes the results of a first phase study in which various auxiliary agents and systems were evaluated for use in aircraft ground fire suppression. The program was sponsored by the Tri-Service System Program Office for Aircraft Ground Fire Suppression and Rescue (ASD/SMF), Wright-Patterson Air Force Base, Ohio under Contract No. F33657-72-C-0422. Mr. Niles Fisher was project monitor. The study was conducted by the Fire and Safety Group at Arthur D. Little, Inc., Cambridge, Massachusetts during the period of 29 November 1971 to 13 March 1972.

This report was submitted by the authors in July 1972. The report has been reviewed and is approved.

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System Program Director
Acft Gnd Fire Suppression & Resc SPO
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ABSTRACT

This program was conducted with the ultimate objective of reducing the number and types of auxiliary extinguishing agents and systems used for aircraft ground fire suppression at military airports.

This phase was devoted to the definition of auxiliary agent/system requirements and to the review of existing knowledge on the performance of various agents and systems under particular fire and environmental conditions likely to be encountered at military airports. Where knowledge was lacking, a series of environmental and small scale fire tests were conducted, the latter on three mockups simulating fires in an aircraft engine, fuel running along the incline of an aircraft wing and a ruptured fuel tank containing reticulated foam.

Candidate auxiliary agents and systems were recommended for the various requirements identified. A test program aimed at reducing the number of agents and systems to a minimum was planned and proposed for the second phase of this project. Two other areas were identified as requiring additional work and recommended for the second phase. These were the development of a more effective magnesium fire extinguishing agent and system, and the optimization of the design of nozzles and delivery mechanisms used on portable and wheeled extinguishers.

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1. INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

A large number of aircraft (including helicopters) fires occur on the ground, particularly during landing and take-off. Quick action by airport and aircraft personnel is essential if lives and property are to be saved. Unfortunately, the types, quantities, locations, and orientations of fuels that may be involved in an aircraft ground fire are so varied that a single fire extinguishing agent or system is not adequate to control all possible fires. Protein foams and aqueous film forming foam (AFFF) are the most commonly used extinguishants for aircraft ground fires since these fires usually involve fuel spills. However, auxiliary agents are required for extinguishing other types of fires. These agents are deployed in various types of dispensing systems. The auxiliary agents and extinguishing systems are either used separately to extinguish specific types of fires or used in conjunction with other agents to gain better control of the fire.

Because several agents and systems may be used for the various fire situations that may arise, there has been a tendency to have available for ground control a large number of combinations of agents and systems. This has presented problems in storage and maintenance and difficulties in selecting the appropriate agent/system for a given fire, particularly by an unskilled person who may be within or near the aircraft. It would thus be highly desirable to select the optimum number and types of extinguishing agents and systems for use in aircraft ground fire control, consistent with a high cost-effectiveness and without jeopardizing the safety of the aircraft, its occupants and attendants.

1.2 OBJECTIVE

The long range objective of this program is to select the optimum combination of agents and systems for aircraft ground fire suppression. The selection was to be made by conducting a study in two phases. A first round of selections was to be made in this study (Phase I) on the basis of a definition of agent/system requirements and a comprehensive

survey of existing data on the performance of extinguishing agents and systems when applied to standard fires and under various environmental conditions. Where data were not available, laboratory tests were to be designed and conducted to indicate the capabilities and limitations of these agents and systems. Plans for final validation of the recommended agents/systems in Phase II were to be proposed as part of this study.

It should be clearly understood that this study was to be devoted to aircraft ground fire suppression and was not intended to cover on-board fire fighting aspects and systems.

1.3 APPROACH

To achieve the objectives of the first phase of the study, we visited and discussed this program with a number of fire extinguishing agent/system manufacturers. We also reviewed the literature published by such organizations as Underwriters' Laboratories, Factory Mutual, National Fire Protection Association, and American Pilots Association, and by Government Laboratories such as the Federal Aviation Administration, Naval Research Laboratories and Wright-Patterson Air Force Base. We discussed airport fire protection requirements with the chiefs of several civilian and military airports (and heliports). We assembled all available data on potential agents and systems including some that were under development, and identified certain gaps in knowledge that required further environmental and fire tests beyond those normally required by approval laboratories. We also defined agent/system requirements for aircraft ground fire suppression and, on that basis, selected the most promising agent/systems that we felt would satisfy these requirements.

This report summarizes our findings. The agent/system requirements for aircraft ground fire suppression are discussed in Section 2. A review of existing knowledge on agents and systems is given in Section 3. The results of the environmental and fire test program are given in Section 4. Our rationale for the selection of the final agent/systems and our conclusions and recommendations are given in Sections 5 and 6, respectively.

2. REQUIREMENTS OF AUXILIARY AGENTS AND SYSTEMS

For some time now, foams, particularly protein and aqueous film forming foams, have been regarded as the primary fire suppression agents in combating aircraft ground fires. However, foams by themselves cannot be considered complete systems for such fires. Often, situations occur where foams are ineffective and the need arises for additional agents and systems that can adequately handle the situation. There are several such auxiliary agents and systems now available or under development with varying degrees of effectiveness and capability. Before examining these agents and systems, it is necessary to establish:

- The kinds and sizes of aircraft ground fires likely to be encountered and which may call for the use of an auxiliary agent;
- The characteristics that are most desirable in an auxiliary agent; and
- The system characteristics that result in the most effective auxiliary agent performance.

2.1 TYPES OF AIRCRAFT GROUND FIRES

To identify the types of aircraft ground fires of most concern, and the fuels that may be involved, we questioned military airport fire chiefs and personnel at Norfolk Navy Air Base, Fort Rucker Army Base, Fort Eustis Army Base, Wright-Patterson Air Force Base, L. G. Hanscom Air Force Base, and Langley Air Force Base as well as the fire chiefs of two civilian airports (Philadelphia and Columbus). We also examined annual reviews of U.S. air civil aviation accidents[1,2] and other studies on aircraft ground fires[3,4,5,6]. We concluded that the three categories suggested by Salzberg and Campbell[3] were not sufficient to describe all aircraft ground fires which are of concern to the three military services. We recommend the following types of aircraft ground fires:

- Two-dimensional fuel spill fires;
- Three-dimensional flowing fuel fires where the fuel may flow over hot objects;
- Aircraft interior fires in habitable compartments.
- Interior fires in non-habitable (cargo) compartments
- Magnesium wheel and brake fires; and
- Stack fires (helicopters)

2.1.1 Two-Dimensional Fires

The two-dimensional spill fires in aircraft ground accidents usually involve fuels such as JP-4, JP-5, AVGAS and to a small extent hydraulic fluids. Such fires, depending slightly on the terrain where the spill occurs, are best suppressed by foams. Protein or aqueous film forming foams can provide quick knock-down and adequate control of these fires. Aqueous film forming foams (AFFF) have been reported[3,5] to be more effective than protein foams in extinguishing experimental large scale fires as well as actual aircraft fires.

2.1.2 Three-Dimensional Fires

Three-dimensional fires involve flowing fuel, multiple levels of elevation, or obstructions in the fire. These features greatly curtail the effectiveness of foam agents. Examples of reported incidents involving such fires on a stationary aircraft on a runway or on a ramp include[7]

- Fire in the main gear prior to take-off.
- Hydraulic oil fire in the wheel well assembly.
- Fuel vent leaked, torched and ignited on engine start.

Engine nacelle fires can be included in this category because generally they can be reached from the outside of the aircraft and quite often they degenerate into a flowing fuel fire. However, engine nacelle fires involve circumstances sufficiently peculiar to warrant consideration as a separate category. Another particular fire which

may involve sufficiently peculiar requirements to warrant separate consideration is that in which the reticulated polyurethane foam used in some aircraft tanks is itself on fire.

This is one category of fires where an auxiliary agent is needed. The combination of fire geometry, height above ground level, and the presence of hot aircraft components that may lead to reignition, limits the usefulness and effectiveness of foams.

2.1.3 Interior Fires in Habitable Compartments

Interior aircraft ground fires within the habitable compartments differ in many respects from interior fires in non-habitable (cargo) compartments. Because they are detected early by the occupants, these fires tend to be smaller in size. They usually involve electrical wiring and furnishings (e.g. seat padding) and can often be extinguished using a small (quart size) portable extinguisher. The presence of personnel in the compartment puts some limitations on the amounts of toxic and irritant products that can be tolerated from extinguishing agents. The primary foam agents may not be effective on these fires.

2.1.4 Interior Fires in Nonhabitable Compartments

These fires can be subdivided into three major types

- Hidden hydraulic oil line fires;
- Fires in the electrical systems; and
- Fires in the cargo compartments.

Hydraulic oil line fires are generally difficult to reach. They occur in the wall or floor spaces of the aircraft and have to be fought usually from the aircraft interior. Fires in electrical systems occurring in the nonhabitable compartment would be quite similar to those occurring in the habitable compartment except that they would tend to grow to larger proportions because they can go undetected for a longer time. Thus they may require the application of a larger quantity of extinguishing agent.

A fire in the cargo compartment probably presents the greatest hazard to an aircraft. The varieties and quantities of solid and liquid fuels that may be present and the possibility that the fire will go undetected for a considerable length of time may lead to an uncontrollable fire particularly in the larger cargo planes. Solid fuels in cargo compartments may consist of corrugated cardboard boxes, wood crates, tires and canvas. Liquid fuels include JP-4,JP-5, AVGAS and hydraulic oil, either in storage containers or inside fueled vehicles being transported. Indeed, it has been suggested that since large cargo planes are equivalent to warehouses, a fixed fire detection, alarm and suppression system (e.g. a halon 1301 system) should be installed to control such fires before the airport fire department arrives at the scene. We believe that this suggestion has great merit and should be considered seriously. However, this would not eliminate the requirement for ground fire fighting agents and systems to combat such fires, and the primary foam agents would have limited effectiveness on these fires.

2.1.5 Magnesium Wheel and Brake Fire

This type of fire has been placed in a separate category because of the complicating presence of magnesium, which, when heated sufficiently, will ignite and is difficult to extinguish. A typical fire would involve one or more wheels, the rubber tires, hydraulic oil from the brake lines and any spilled fuel that may also be present. The burning liquid fuels and tires can be extinguished by conventional auxiliary agents once the magnesium is extinguished.

2.1.6 Stack Fires

In our discussions with army heliport fire chiefs, fires in the engine exhaust stacks of helicopters were mentioned as fairly frequent. These fires apparently occur due to fuel flooding, evaporation and subsequent ignition. They are generally easily extinguished with a portable CO_2 extinguisher. Primary foam agents are generally ineffective on these fires.

2.2 SIZES OF AIRCRAFT FIRES

Just as much as the type of a fire determines the choice of an effective fire extinguishing agent for that fire, the size and geometry of a fire determines the agent dispensing system characteristics which are most desirable. The system must be capable of dispensing the extinguishing agent in the most effective manner to the fire area. The dispensing system must have adequate distance of throw, angle of spread and agent capacity and discharge rate. Therefore, it is important to know what the typical sizes of exterior and interior aircraft ground fires are so that an appropriate dispensing system may be chosen.

2.2.1 Exterior Ground Fires

Two approaches are possible in assessing the size of an exterior ground fire requiring auxiliary agents and systems. The first, an accurate detailed assessment, would consist of developing a matrix consisting of a list of common aircraft expected at a particular air field and listing for each aircraft the potential areas of fires involving a single engine, several engines, the wings, wheels and the whole aircraft. This matrix could further list for each fire the type and amount of agent needed to extinguish that particular fire. Complete information regarding agent type and quantity needed to extinguish the fires listed above is not available at present but may be developed from the results of Phase II of this program.

Such a detailêd assessment, however, may not be of much practical value in actual field use. Situations would arise where there would not be sufficient time in an emergency to consult such a guide and to act accordingly. In many cases, the airport fire brigade would have to provide stand-by services prior to the actual landing of a malfunctioning aircraft and would have no way of assessing the expected fire size requiring auxiliary agents with any certainty.

The second approach, which provides a quick field assessment of the fire size and which can be used as a rule of thumb may be more appropriate in actual practice. This assessment assumes that for any given aircraft the most probable fire size requiring auxiliary agents is equivalent to the complete area of one wing. If the total wingspan is L and the aspect ratio for each wing is 10 we would have, for any craft, a typical fire size equal to $\frac{L^2}{20}$ in area. This fire area may not be in one location and may be spread out over the aircraft in two or more locations. Admittedly, this is a crude approach for estimating the fire size requiring auxiliary agents but should be adequate in view of the uncertainties in other aspects of this fire problem such as ambient environmental and terrain conditions, training of field personnel, amount of fuel on board the aircraft, etc.

It is curious to note, that a completely different semi-empirical approach to this problem results in an expression for fire size requiring auxiliary agents very similar to the one mentioned above. This second approach is based on experimental and actual ground fire observations.

In general, the probable maximum dimensions of an exterior ground fire can be estimated from the dimensions and configuration of the aircraft and the amount of combustible material involved in the fire. In a recent survey of a large number of crash fires and simulated crashes[2,4,7] incidents were reported which had sufficient photographic coverage as to allow estimation of the fire size relative to the dimensions of the aircraft involved. A study of the resulting data determined that the maximum fire dimension in any of these incidents was 0.75 of the product of the fuselage length and the wingspan. In all but two of the incidents, the total fire area was found to be less than 0.60 of this product. Thus, it was concluded that a reasonable maximum expected dimension of such a fire would generally be an area 2/3 the product of the span and fuselage length. It was further noted that this calculated total area will encompass all but the most extreme cases and has been used for establishing crash truck extinguishing capability requirements.

A criterion which is commonly used to evaluate vapor securing extinguishing agents (foams) is the time or quantity of agent required to secure 90 percent fire control. This has been shown to be a realistic indication of the portion of the fire area a primary agent (foam) can efficiently control and extinguish. Beyond this limit, experiments have shown[8] that for each 100 gallons of foam used to attain 90 percent control, 60 to 70 additional gallons are required to extinguish the remaining 10 percent. It is this 10 percent upon which foams are relatively ineffective that requires auxiliary agents. This suggests that the minimum amount of auxiliary agent required is that needed to extinguish a total fire area of 1/15 (or 2/3 x 10%) the product of the fuselage length times the wingspan of an aircraft involved in a major ground fire. Since the fuselage length and wingspan are both about the same length (L) for most aircraft (especially medium and large ones) the expression for fire involvement becomes $L^2/15$. This is to be compared with the $L^2/20$ obtained above. Once again, this total fire area may include fires of several different types either concentrated in one area or scattered. The actual amount of agent that is required will depend upon the severity of the fire(s) to be encountered in this area, and will thus depend on the type(s) of fuels burning, environmental factors, and the rate(s) of flow of fuel(s) into the fire area.

The range of throw of a fire extinguishing system is a function of the maximum fire area to be expected, the height above ground that the burning aircraft component is located, and the prevailing wind conditions during the fire. In general, once the primary fire is under control, fire fighting personnal enter the foamed spill area to reach the remaining auxiliary fires. The required range of throw of an auxiliary system need not be more than two times the approximate engine height. A factor of two is included for safety as under many conceivable conditions it may not be prudent to get too close to an aircraft engine on fire. Using this criteria, the maximum throw distance required of an auxiliary extinguishing system would be about 32 feet for the C-5.

Table 2.1 shows recommended optimum fire areas that have to be handled by auxiliary agents after an exterior ground fire has been partially extinguished with foam. The table also shows recommended ranges of throw which are desired from auxiliary extinguishing systems for three classifications of aircraft sizes.

2.2.2 Interior Fires

Fires in the habitable and cargo compartments of an aircraft generally demand the use of an auxiliary agent. Thus, it is necessary to determine the requirements which an agent system must fulfill in this type of fire situation. To do so it is convenient to classify military aircraft into small, medium and large sizes as was done in Table 2.1 and to find the approximate maximum enclosure volume for each classification that may be involved in a fire. The results are shown in Table 2.2. The results suggest that typical volumes of aircraft compartment are 25, 800-1,000 and 2,000-34,000 cu ft for small, medium, and large aircraft respectively.

It is evident that for small aircraft there is a very limited amount of cabin and cargo space (if any at all). Many fires in a small aircraft can be and indeed have been extinguished by a small (quart size) portable extinguisher which may be carried in the aircraft. However, ground fire fighters should be equipped with larger extinguishers.

For medium aircraft, larger extinguishers may be needed. Here the 1 or 2 gallon or 20 to 30-lb extinguisher sizes appear necessary.

Larger aircraft, however, present very serious problems to ground fire fighting personnel - the kind of problem that a fire fighter faces when he enters a burning unprotected warehouse. It is doubtful that portable or wheeled auxiliary agents and systems brought in from the outside of large aircraft will be of much use if a fire in the interior had progressed unchecked for a long time. The accumulation of smoke and toxic products of combustion and the relative inaccessibility of the fire prevent ground fire fighters from controlling such fires

TABLE 2.1

MAXIMUM REQUIREMENTS OF AUXILIARY AGENT/SYSTEMS FOR EXTERIOR GROUND FIRES

Aircraft Size	Approximate Engine Height (ft)	Length (ft)	Wingspan (ft)	Averaged Fire Area (ft^2)	Averaged Range (ft)
Small					
U.S. Army U-8F	5	36	46	140	13
USAF F-105	7	69	35	(12' x 12')	
USAF F-4	7	58	38		
Medium					
USAF DC-9A	9	119	93	990	17
USAF VC-137 (Boeing 707)	8	150	145	(32' x 32')	
U.S. Navy P-3	9	117	100		
Large					
C-5	16	248	223	3,350	27
Boeing 747	11	231	196	(58' x 58')	

TABLE 2.2

TYPICAL CABIN SIZES OF AIRCRAFT

Aircraft Size	Cabin Length (ft)	Cabin Width (ft)	Cabin Height (ft)	Cargo Space Fwd. (ft^3)	Cargo Space Rear (ft^3)
Small					
U.S. Army U-8F	19.5	4.3	4.8	22	
Medium					
USAF DC-9A	56	10	7	Under floor 600-1019	
USAF VC-137 (Boeing 707)	107	12	7.5	680-835	865-910
Large					
C-5	Upper deck, fwd. 39	14	7.5	2010	--
	Upper deck, aft 60	13	7.5	--	6020
	Lower deck 144	19	13.5	34,745	
Boeing 747	185	20	8.3	2890	2450

effectively. The injection of large quantities of CO_2 from a 4,000 lb truck through a wall penetration into the burning compartment has met with limited success.

In our discussions with fire chiefs of various military airports, it was suggested that fixed aircraft fire suppression systems are the solution to this problem. Protection could be in the form of fixed or modularized halon 1301 or CO_2 systems, or even a water sprinkler system. The use of halon 1301 instead of CO_2 as an auxiliary agent in fire trucks has also been suggested and may be worth considering further. However, the limited holding power of these agents when not confined must also be considered, and ground fire fighting agents are required whether or not a fire fighting system is installed in the aircraft.

2.3 IDEAL CHARACTERISTICS OF AN AUXILIARY AGENT

The following are the most important characteristics expected of an ideal auxiliary agent for aircraft ground fires:

- The agent should be effective in extinguishing the fire by providing quick knockdown of flames, early fire suppression and prolonged securing against reignition.
- The agent must be capable of extinguishing fires involving the variety of combustible cargo and liquid fuels encountered aboard an aircraft as well as electrical fires.
- Since many aircraft ground fires are likely to be caused by a fuel spill and the fuel spill fire would be primarily extinguished by foam, the auxiliary agent used for the remaining fires must be fully compatible with foam. Also, auxiliary agents are often employed on such fires by personnel on the scene prior to arrival of foam trucks, with foam being employed after arrival of the trucks to complete extinguishment and/or provide a vapor securing blanket. In either case, the auxiliary agent must be compatible with foam.

- The auxiliary agent should withstand prolonged storage and should operate under the environmental extremes to which it may be exposed when used by the military services.
- The physical and chemical properties of the agent should be such as to produce a minimum of detrimental corrosive effects on materials normally used in aircraft structures and fire fighting equipment.
- The agent and its products of decomposition in a fire environment should be as non-toxic and nonirritating as possible to fire-fighting and aircraft personnel, both in the open and in confined spaces.
- The agent should be cost-effective. The cost effectiveness of an agent will depend largely on agent cost, agent system cost, quantity needed for fire suppression, shelf life of the agent, and the versatility of the agent in being effective on many kinds of ground fires. Agent storage servicing and maintenance requirements are also important in determining the cost effectiveness of an agent.
- It is particularly important that agents used in engine, electrical and engine exhaust stack fires be "clean agents," i.e., that they not leave deposits which are abrasive or otherwise cause degradation of performance of aircraft or components.
- Application of the agent should not create or increase visibility problems for fire fighters.

2.4 IDEAL CHARACTERISTICS OF AN AUXILIARY SYSTEM

The system which dispenses a particular auxiliary agent is just as important to the overall fire fighting task as the agent itself. An ideal fire suppression system should display the following characteristics:

- The system must be capable of dispensing the agent appropriate to the type of fire.

- The system must be capable of delivering this agent at the flow rate required to efficiently extinguish the fire.
- The system must have sufficient range to deliver the agent to the fire from a safe distance and in an effective pattern.
- The system must have sufficient agent capacity to extinguish the fire.
- The system should be of simple design to ensure ease of maintenance and a high degree of reliability under fire conditions.
- The system must be capable of withstanding prolonged periods of environmental extremes without losing its reliability or effectiveness.
- The system must be sufficiently human-engineered to allow the operator(s) ease of mobility and operation under fire conditions and good control over the direction and flow-rate of the agent being expelled.
- The system must be cost-effective by having a low initial cost and sufficient shelf-life to remain reliable and effective over long periods of disuse with minimum maintenance.
- The system must permit quick refilling without unnecessary complications or excessive costs.

It is unlikely that any one agent or system will display all of these characteristics. Section 3 summarizes the known properties of existing commercial and developmental agents and systems. Section 4 supplements this data with the results of tests that we found necessary to conduct under this study to fill certain gaps in knowledge on agent and system properties.

3. REVIEW OF STATE-OF-THE-ART

3.1 SOURCES OF INFORMATION

To assemble information on the capabilities of commercially available fire extinguishing agents and systems, a large number of representative manufacturers were visited and interviewed. The literature published by NFPA[9, 10], Underwriters' Laboratories[11, 12], Factory Mutual[13], reports from Government test facilities such as FAA[5] and Naval Research Laboratories[8, 14] and final contract reports[15,16] for agencies at Wright-Patterson Air Force Base were reviewed.

At the conclusion of this search one could not help but form the impression that, except for very few instances, the fire extinguishant/extinguisher industry has been relatively lethargic. The prolonged process of commercial and military certification and approval of new extinguishing material and equipment does not encourage research in this field. The fire industry which is indirectly and inadvertantly controlled by the insurance industry which, in turn is inherently conservative, operates under the premise: "We know that this works, why take a gamble on something new?"

Thus, it is not surprising that most of the "research" effort currently underway by the fire industry is directed towards superficial improvements in the performance of existing extinguishants and hardware. Modification of extinguishant fire properties, and changes in extinguisher valve design and container wall materials are typical examples of current research activities. We did identify a few new products which are claimed to be radically different in behavior and chemical structure and which display greater effectiveness than existing extinguishing agents.

In this section we present our review of the state-of-the-art of existing auxiliary agents and systems, their fire fighting capabilities, and their limitations, and our identification of areas of weakness or gaps in knowledge that we felt needed to be filled in this phase of the study.

3.2 AVAILABLE AUXILIARY AGENTS

Auxiliary extinguishing agents have been classified in many ways. One classification divides them into: dry chemicals, halogenated agents, combustible metal agents, and a variety of other agents such as water and carbon dioxide. These agents are identified and discussed below and summarized in Table 3.1.

3.2.1 Dry Chemicals

Dry Chemicals are believed to extinguish fire by attenuating thermal radiation from the flame to the fuel surface and by chemical inhibition. They have been recognized for their ability to knockdown and extinguish fires in flammable liquids quickly. They have also been successfully used for fires in some types of electrical equipment. One type, monoammonium phosphate has been shown to be effective on fires in ordinary solid combustibles because it melts and seals the burning surface from oxygen. Dry chemicals currently used by the military and commercially available include:

- Potassium bicarbonate, Purple K (PKP) - per Military Specification MIL-F-22287
- Monoammonium phosphate (MAP)-Dry Chemical per Military Specification MIL-F-23555
- Sodium bicarbonate - Foam Compatible Dry Chemical (CDC)- per Military Specification MIL-F-19563
- Potassium chloride - Super K

Others which are under development or will be commercially available shortly include:

1. Monnex - a recent departure from the single salt plus additives concept used in the formulation of other dry chemicals. This agent, produced by Imperial Chemical Industries (ICI) of the United Kingdom, contains a combination of urea and at least one active fire-extinguishing agent selected from salts and hydroxides

TABLE 3.1

AVAILABLE AUXILIARY AGENTS

Agent	Agent Type	Cost ($per lb.)	Fire Type
Potassium Bicarbonate (Purple K or PKP)	Dry Chemical	.49	B,C
Monoammonium Phosphate (MAP or ABC)	" "	.47	A,B,C
Sodium Bicarbonate	" "	.16	B,C
Potassium Chloride (Super K)	" "	.45	B,C
"Monnex" (ICI)	" "	1.00	B,C
"Ansul X" (Ansul Co.)	" "	Experimental	B,C
Bromochloromethane (CB)	Halon	.57	B,C
Bromotrifluoromethane (1301)	Halon	2.91	B,C
Dibromotetrafluoromethane (2402)	Halon	3.70	B,C
Bromochlorodifluoromethane (1211)	Halon	1.69	B,C
Halon Foam (ADL)	Halon mixture	Experimental	A,B,C
Carbon Dioxide (CO_2)	Liquefied Gas	.16	B,C
Water/antifreeze	Liquid	.29	A
Met-L-X	Dry Powder	.26	D
Trimethoxyboroxine (TMB)	Liquid	1.40	D

of alkali metals. In a fire, this powdered chemical decrepitates, i.e., breaks up into much finer particles, and its effectiveness is thus greatly enhanced.

2. Ansul X - an improved potassium bicarbonate base agent currently under development by the Ansul Co.

3.2.2 Halogenated Agents

Two halogenated agents are being currently used by the military. The first, bromochloromethane (CB or Halon 1011), is widely used in one quart (A-20) portable extinguishers carried aboard military aircraft. The one and two gallon (D-2) units are used for airport ground fire-fighting purposes. The other, bromotrifluoromethane (Halon 1301), was developed for extinguishing aircraft engine fires. Some portable extinguishers have been developed for local application to flammable liquid and electrical fires.

These and other halogenated agents inhibit the flames by dissociating into halogens and hydrogen halides that break the reaction chains of the oxidation reaction and thereby reduce the rate of heat generation to such a level that the fire is extinguished. Other halogenated agents which have been used outside the U.S. include:

- Bromochlorodifluoromethane (Halon 1211). This agent is widely used in Europe, the Far East, and Australia. It is used in fixed and portable system in aircraft. It has recently become available in quantity in the USA from ICI, its major foreign producer.

- Dibromotetrafluoromethane (Halon 2402) is currently being offered as a fire-extinguishing agent in Europe by Montecatini Edison (Milan, Italy). Although this agent is quite effective on liquid fuel fires it is more expensive and has a higher toxicity than halon 1301 or 1211.

In a recent study by this laboratory for the United States Air Force, a foaming mixture consisting essentially of halon 1301, halon 1211, and a surfactant was developed which was a much more effective

fire extinguishant than CB and which had a lower toxicity. Extinguishers (one quart and 2 gallon sizes) have been developed to dispense this self-foaming mixture[15,24].

3.2.3 Metal Extinguishing Agents

Magnesium used in aircraft wheel castings occasionally ignites during aircraft ground fires, particularly if the fire involves the wheel, tire and brake assembly. A number of substances have been evaluated, recommended, tested, and used for extinguishing burning metals. Only two commercially available magnesium extinguishing agents can be dispensed from portable or wheeled extinguishers. These are trimethoxyboroxine (TMB) manufactured by the Callery Chemical Company and Met-L-X manufactured by Ansul. The first, (TMB) is a combustible liquid which breaks down to produce a molten layer of boric oxide on the surface of the burning magnesium thus preventing contact with air.

Met-L-X is a sodium chloride base powder containing additives to improve flow characteristics and to bind together the salt particles into a solid mass under fire conditions. It functions by excluding air from the burning metal surface. In both cases, large quantities of agents are required for effective extinguishment.

3.2.4 Carbon Dioxide

Carbon dioxide (CO_2) is an agent which has been used for many years to extinguish liquid fuel fires and electrically energized equipment fires. Being an inert gas which is 1.529 times as dense as air under normal conditions, it effects extinguishment by diluting oxygen to a concentration which cannot support combustion, blanketing, and to some extent by the cooling effect produced by the sublimation of the dry ice which is produced when it is expelled from an extinguisher.

3.2.5 Water

Water is not generally considered an auxiliary agent because foam trucks usually have the capability of dispensing water just as well. The principal limitation for its use as an auxiliary agent for aircraft

ground fire suppression is its relatively high freezing temperature. Nevertheless, by the use of antifreeze additives, commercial portable extinguishers are available which will not freeze at -40°F. The U.S. Naval Research Laboratory developed an extinguisher containing a lithium chloride solution which will function at -65°F. However, the corrosive effect of LiCl prohibits its use for aircraft fire suppression.

3.3 AVAILABLE AUXILIARY EXTINGUISHING SYSTEMS

3.3.1 Classification of Auxiliary Systems

Auxiliary extinguishing systems can be divided into three classifications based on their weight which in turn governs the manner in which they are handled. These classifications are:

- Portable
- Wheeled
- Truck mounted

Each classification is in turn subdivided into smaller units depending on the weight or volume of agent used. Portables come in sizes which range from 2 1/2 to 30-lb for dry chemicals or one quart to 2 1/2 gallons for liquid agents. Wheeled extinguishers range from 50 to 350-lb while truck mounted units range from 500 to 4,000-lb.

A different way of classifying auxiliary systems depends on the manner in which the extinguishant is expelled from the systems. These can be classified into two categories:

- Stored Pressure Extinguishers: Here the agent is pressurized by virtue of its own vapor pressure or with a propellant gas; and

- Cartridge or Tank Pressurized Extinguishers: where a separate cartridge or tank containing the propellant gas is punctured or opened when the extinguisher is to be used. The expelled propellant gas pressurizes another tank containing the extinguishant to be dispensed.

To some extent, the design of an extinguisher varies from one extinguishant to another. For example, materials of construction are governed by the corrosion potential of the agent, while the thickness of the extinguisher wall is controlled by the maximum operating pressure. The nozzle and valve design also vary since they depend on the manner in which each agent is most effectively dispensed on a fire.

3.3.2 Dry Chemical and Dry Powder Extinguishers

Portable dry chemical extinguishers are available in stored and cartridge pressure types. The operating lever of a stored pressure extinguisher is generally mounted on top of the cylinder and requires that the operator both lift and control the flow rate of agent with one hand while directing the extinguishant stream or nozzle at the end of a hose with the other.

In the cartridge type, the agent compartment is not pressurized until a puncture lever is depressed, breaking the seal of the cartridge. Except for small extinguishers, an operating valve is located at the end of a hose. The operator lifts the unit with one hand and controls the agent flow rate and direction with the other.

Both types of portable extinguishers are available in sizes ranging from 2 1/2 to 30-lb agent capacity.

Above 30 lb, the total weight of a unit becomes unmanageable and the extinguisher has to be wheeled. These units are available in sizes ranging from 50 to 350-lb agent capacity and are available as either stored pressure units or as exterior propellant gas nitrogen cylinder driven units. Depending on their location and use, a variety of wheels are offered and generally a 50-ft hose with an operating lever on the end is provided. The propellant gas pressure and other features will vary with the manufacturer.

Units larger than these are usually mounted on trailers or skids on the back of trucks and are available in sizes which vary from 500-lb to 2,500-lb agent capacity. These typically have one or two hand

hoses and/or a deluge system and usually are pressurized by one to five nitrogen cylinders. Some are available as twin agent systems with up to 200 gallons of AFFF concentrate being incorporated into a system with 1,350-lb of dry chemical.

Met-L-X dry powder is commercially available in a 30-lb portable unit and 150-lb and 350-lb capacity wheeled units. The portable extinguisher utilizes an outside cartridge of CO_2 while the larger units have exterior nitrogen cylinders.

3.3.3 Liquefied Gas Extinguishers

Liquefied gas portable extinguishers are of the stored pressure type since the agent itself will provide all or most of the necessary pressure. CO_2 portable units have the operating valve on the cylinder with a large discharge horn at the end of a hose or a metal pipe with a moveable connection.

Halon 1301 and halon 1211 portables are somewhat similar except that halon 1301 is stored at higher pressures (360 psi) while halon 1211 is stored at 110-175 psi.

Both halon 1301 and halon 1211 units are generally pressurized with nitrogen to boost their discharge pressures at low temperatures. For example, halon 1301 has a vapor pressure of 199 psig at 70°F, but this drops to only 17.2 psig at -40°F and to 2.91 psig at -65°F. Thus, nitrogen is needed for proper operation at these temperatures.

The only portable halon 1301 extinguisher commercially available is of a 2 1/2-lb agent capacity and was specifically designed for electrical fires, while a variety of European manufactured portables are available for halon 1211 with a maximum agent capacity of 25 lb.

Larger units for some of these liquefied gases are also available, though not in the variety of sizes available for dry chemicals. Carbon dioxide wheeled units come in sizes ranging from 50 to 750-lb agent capacity, and 4,000-lb capacity trucks are available and used at some military airports as an auxiliary agent. Halon 1211 is available in a 110-lb

capacity wheeled unit, while halon 1301 is not available in wheeled units because of its limited usefulness for local application.

3.3.4 Liquid Extinguishers

Extinguishers for agents which are liquid at normal temperatures and pressures are either pressurized with nitrogen in the head space or with a cartridge of CO_2 or N_2.

Portable water (with antifreeze) extinguishers range in size from one quart to 2 1/2 gallons. Larger units are not generally made. The smaller units are mostly used on board civilian aircraft.

CB portables come in one-quart (A-20), one gallon (D-1), and two gallon (D-2) units. The one-quart units are used aboard military aircraft while the other two are used as auxiliary systems for ground fire suppression.

The two larger portables have two sets of operating valves, one on the cylinder and one on the hose. Depressing the valve on the cylinder alone gives a stream of agent, while depressing both valves results in a spray. Wheeled CB extinguishers of 150 to 350-lb capacity are available and are generally used as auxiliary systems for aircraft ground fires at military airports.

TMB, one of the combustible metal agents, is primarily used in a 2 1/2 gal stored pressure extinguisher which was developed by the Department of the Navy. This extinguisher has not been manufactured for a number of years, but no major difficulties would be expected in modifying other types of extinguishing systems for use with this agent.

3.4 AGENT FIRE FIGHTING CAPABILITIES

3.4.1 Dry Chemicals

Standard tests that have been used on the majority of commercial extinguishing agents to date are those conducted by Underwriters' Laboratories (UL). The UL test for a Class B rating consists only of a flammable liquid pan fire. This is a fairly simple fire test which is not designed to compare the effectiveness of agents. Neither is it

designed to indicate the reliability or applicability of the agent in combating the more difficult fire geometries which may be encountered in real-life such as an aircraft ground fire. In the absence of other information, a comparison of the UL ratings assigned to each agent used in similar extinguishers under the same fire conditions does provide some indication of relative effectiveness.

Table 3.2 gives the dimensions and other pertinent data of the UL standard liquid fuel fire tests required for each rating. Table 3.3 compares the effectiveness of a number of dry chemical extinguishants and CO_2 on flammable fuel pan fires. It also shows the approximate agent cost per unit area of fire extinguished. These results suggest that, from a fire extinguishing effectiveness standpoint, these agents are ranked: Monnex, potassium bicarbonate, potassium chloride, sodium bicarbonate, monoammonium phosphate and CO_2 in that order. Ansul X was claimed to have a higher effectiveness than potassium bicarbonate, but no data were available on how it compared with Monnex or PKP.

From an agent cost-effectiveness standpoint, it is interesting to note that Monnex, which costs about \$1.00/lb, is roughly equal to potassium bicarbonate which sells at about \$.49/lb.

For aircraft ground fire suppression, it would appear that dry chemicals could be useful on liquid fuel spill fires as well as some electrical fires. These agents are not desirable for use on fires in engines or in electrical equipment with moving parts such as relays or motors because the residue will require that the affected part be dismantled and thoroughly cleaned. The relative effectiveness of these agents on realistic aircraft fire simulations was an area that required further investigation in this phase of the study.

3.4.2 Halogenated Agents

Information gathered concerning the flame inhibiting capabilities of the halons is in many cases contradictory. For example, the results of experiments using the explosion tube technique[17], in which the concentration of the agent required to prevent the ignition of a methane-air mixture was determined, indicated that the order of decreasing effectiveness (on a weight basis) was halon 1211, halon 1011

TABLE 3.2

STANDARD UL FLAMMABLE LIQUID FIRE TESTS

Classification and Rating	Minimum Effective Discharge Time, Seconds	Pan Size, Square Feet (Inside)	n-Heptane Used, U.S. Gallons* (Approximate)
Indoor tests:			
1-B	8	2 1/2	3 1/4
2-B	8	5	6 1/4
5-B	8	12 1/2	15 1/2
10-B	8	25	31
20-B	8	50	65
Outdoor tests:			
30-B	11	75	95
40-B	13	100	125
60-B	17	150	190
80-B	20	200	250
120-B	26	300	375
160-B	31	400	500
240-B	40	600	750
320-B	48	800	1000
480-B	63	1200	1500
640-B	75	1600	2000

*The amount of n-Heptane to be used in each test is to be determined by the actual depth as measured in the pan and not by the gallons indicated.

TABLE 3.3

COMPARISON OF AGENT EFFECTIVENESS

	Portable Unit Capacity (lb)	UL Rating	\$/sq ft (for B-fire)
Potassium Bicarbonate (Purple K)	18	60B:C	.059
	27	80B:C	.066
Monoammonium Phosphate (MAP)	17	4A:40 BC	.080
	25	6A:60 BC	.078
Sodium Bicarbonate	20	40B:C	.032
	30	60B:C	.032
Potassium Chloride (Super K)	20	60B:C	.060
Monnex (ICI)	18	120B:C*	.060
	26	160B:C*	.065
Ansul X (Ansul Co.)	20	Not available	--
	30	" "	--
Carbon Dioxide (CO_2)	20	10B:C	.128

*Claimed by manufacturer

(CB), and halon 2402. Another series of experiments[18] in which the flammability peaks were determined, showed the decreasing order of effectiveness to be halon 1301, halon 1011, halon 2402 and halon 1211.

In larger scale tests on a 20-ft pan fire, halon 1301 was rated better than halon 2402 which in turn was better than halon 1011 (CB) when the agents were expelled at 800 psig initial pressure. In a similar test, halon 1211 and halon 2402 performed almost identically when expelled at 400 psig initial pressure, but halon 1301 performed much better than either one[9].

These data suggest that small scale laboratory studies may not be of value for determining an absolute relative effectiveness for halogenated agents. The reliability and effectiveness of an agent is best determined on outdoor or indoor fires simulating the realistic fire situations that may arise where the agent is to be used.

CB has been used successfully to extinguish aircraft engine fires and small electrical fires. Studies by ICI[19] suggest that halon 1211 can be used wherever CB is used without jeopardizing the safety of the operator since halon 1211 is less toxic than CB[9]. Other studies on halon 2402[20] show that it is equally effective for local applications. However, recent studies indicate that it may present a more severe health hazard to the operator. The effectiveness of halon 1301 for local application particularly on deep seated fires is very poor because unlike CB, halon 1211, and halon 2402, which are applied to a fire as liquid, halon 1301 is dispensed in gaseous form. As such, its residence time at the site of a fire is limited by the rate and quantity of the agent applied as well as by local convective currents. It is, however, highly effective in total flooding applications. This information suggests that the effectiveness of halon 1211 should be compared with that of CB for local application in aircraft ground fires. Halon 1301 should be considered for total flooding applications in aircraft cargo compartments, particularly in the larger aircraft. Halon 1301 may be applied by a fixed system or introduced by firefighters through a penetration in the aircraft wall from a tank truck.

3.4.3 Magnesium Extinguishing Agents

A study[16] of liquid agents used to extinguish metals compared the amounts of agents required to extinguish and cool a given amount of burning metal to below its ignition temperature. The study showed that large amounts of agents with high cooling capacity were required and that extinguishment times were between 20-30 minutes. Another study[14], compared TMB with other metal agents on the same basis as in the previous study and mentioned that water and foam can be used to cool down the hot mass of metal once the burning area had been covered with an air-excluding coating.

Our review of the literature has shown that not much research has gone into the development of more effective agents for magnesium (as well as other metal) fires. It would appear that a systematic study is needed in which the basic requirements of aircraft magnesium fire extinguishants are identified and the effectiveness of a number of materials satisfying these requirements investigated and compared with TMB and Met-L-X. Salts, eutectic salt mixtures, and salt/liquid suspensions of the halides of calcium, magnesium, manganese, barium, potassium, sodium and aluminum, the fluoborates and silicates of these elements and the oxides of boron and other metals are examples of agents recommended for further study.

3.4.4 Carbon Dioxide

Carbon dioxide effects extinguishment mainly by reducing the oxygen concentration of the air to a level which can no longer support combustion. For the types of fuels commonly used by military aircraft, the minimum theoretical concentration of CO_2 required for extinguishment in an enclosure is 28%.

As with some of the halogenated agents, its use at low temperatures is curtailed by its low vapor pressure. Nitrogen can be used to insure a proper rate of discharge, but no units are commercially available for use at temperatures below -40°F.

Because it is discharged as a solid-gas mixture, its effectiveness for extinguishing outdoor fires can be greatly curtailed under wind conditions. The necessary concentration cannot be maintained over large areas for a long time. If the fire is not extinguished, the flames can quickly spread back to those areas where the CO_2 concentration has dropped. Thus, in order to achieve extinguishment of liquid fuel spills, large capacity, high discharge systems are required. This problem is of course shared by all agents discharged as a gas over an outdoor fire area.

For fires in interior compartments, carbon dioxide has demonstrated excellent effectiveness as a total flooding agent and has been used for extinguishing aircraft cargo fires. It is also used for extinguishing helicopter engine stack fires and is an excellent agent for extinguishing electrical fires.

3.4.5 Water

The extinguishing and physical properties of water are well known. It has been used on fires in ordinary combustibles (e.g. wood, paper, canvas, and cotton) for centuries. Nevertheless, it is a highly inefficient agent. It has been estimated that only 1/9th of the water directed to a fire generally goes into extinguishment while the remainder runs off to unaffected areas.

Much work has been done to improve the efficiency of water with antifreeze, wetting, gelling, and thickening additives which have met with varying degrees of success. As mentioned earlier, since water is available as a primary agent during aircraft ground fires, it can be used for extinguishing aircraft class A (ordinary combustibles) fires in cargo and habitable compartments.

3.5 SYSTEM FIRE FIGHTING CAPABILITIES

The selection of delivery hardware is as important a consideration as the selection of the agent used on a particular fire. To a large extent, the relative effectiveness of an agent applied in similar

hardware on difficult fire geometries, can detemine the capacity that may be required. Nevertheless, the differences in capabilities of the delivery systems in regards to their effective range, reliability, ease of mobility, and ease of operation can make critical differences in the effectiveness of an agent used in two similar capacities but otherwise different systems.

If fire-fighting personnel are incapable of reaching a fire because of height or obstacles, the effective range of the system can be of primary importance. Cartridge-operated portable dry chemical extinguishers generally have a 12 to 18 ft range in 10-lb capacity models and a 17 to 23 ft range in 20- and 30-lb capacity models. The range of stored pressure models increases with the pressure to which it is pressurized. One manufacturer's units are pressurized to 195 psi and are capable of ranges identical to those given above. Another company's units are pressurized to 350 psi and are thus capable of 30-40 ft ranges for most dry chemicals, and 20-25 ft ranges for Purple K. The same kind of considerations apply to larger equipment. A wheeled stored pressure unit is capable of reaching a range of 80 ft while a twin cylinder system of similar capacity is capable of 30-40 ft range only. It is interesting to note that a 40 ft range model of one wheeled extinguisher has one half the UL rating of another with a similar capacity and a 30 ft range indicating the variety of products and capabilities available in the market.

The question of range also brings up the question of available pressure at temperature extremes. CO_2 charged units become virtually ineffective at temperatures below -40°F while nitrogen pressurized units are capable of effective operation at -65°F. Thus, for military applications, nitrogen is the recommended propellant gas.

The nozzle configuration of an extinguisher determines the range, its stream pattern, and thus the extinguisher effectiveness. A proliferation of nozzle shapes and sizes seems to be in use with no formal study having been conducted into what type of nozzle may be the most effective for a particular agent system. Discussions with

fire-fighting personnel have indicated a large amount of confusion over this issue and it appears to be a subject that requires future study.

Range considerations involving the halons are somewhat more complicated because of the physical properties of the agents themselves. For example, because of its boiling point, halon 1301 is a liquefied gas agent which provides for immediate dispersion in the fire area,at the expense of reach or range. Halon 1211 on the other hand has a much higher boiling point and is capable of being projected as a liquid for a greater range. Halon 1011 (CB) is a liquid at a much higher temperature than halon 1211 and thus, is capable of long ranges, but this is at the expense of somewhat difficult and slow dispersion which can limit the effectiveness of the agent.

The TMB extinguisher developed for the Department of the Navy has a straight stream maximum range of 25 feet and a spray range of 15 feet. The portable Met-L-X extinguisher is capable of an 8-ft range while the wheeled units are capable of 14-ft ranges.

3.6 ENVIRONMENTAL CAPABILITIES AND REQUIREMENTS OF AUXILIARY AGENTS

Auxiliary agents must be capable of withstanding the environmental conditions to which they may be subjected. Any significant changes in their performance characteristics or physical properties which may decrease their fire fighting effectiveness or the reliability of their hardware cannot be tolerated. For this reason, both Underwriters' Laboratories and the military services require that each agent satisfy a series of tests.

The tests required by UL for dry chemical agents are briefly described below.[14]

1. Elevated Temperature Test: a sample of the agent is maintained at a temperature of 140°F (60°C) for one week, then allowed to cool for three days, and examined for evidence of caking. Any lumps present are to be dropped from a height of four inches onto a smooth hard surface to determine that they are friable.

2. Hygroscopicity Test: Samples of the agent are placed in a humidity jar at 70 ± 5°F and a relative humidity of 80 percent. Some samples are weighed at the end of each week for three weeks to determine their gain in weight. Other samples are alternated every two days between the humidity jar and a desiccator jar containing anhydrous calcium chloride for a period of three weeks with frequent observations made for caking of the agent. Any lumps found are to be dropped onto a surface as in the elevated temperature test.

3. Water Repellency Test: Weighed portions of the agent are covered with given amounts of distilled water, allowed to sit for two minutes, and poured out of their beakers. The beakers are then dried in a 140°F oven for one-half hour, cooled in a desiccator, weighed, and the percentage by weight of the agent retained in the beakers calculated.

4. Fineness Test: An amount of agent is placed in a sieve shaker unit and the machine operated until the weight of sample retained on each sieve changes less than three grams after a 10 minute operation period.

5. Dielectric Withstand Test: Voltage is supplied from a transformer energized from a suitable low-voltage source to a test cup constructed in accordance with ASTM D877-67. After shaking the cup for 15 min , voltage is applied and increased until the dielectric breakdown voltage is reached as indicated by a continuous discharge across the gap between the electrodes.

It should be noted that the fineness and water repellency tests given above are conducted only for identification purposes, while the agent must display certain capabilities to satisfy the requirements of the other tests.

Environmental tests which the agents must satisfy for military use include:

1. Storage at temperatures from -80°F to +160°F

2. Relative humidity up to 100%

3. Fungus growth as encountered in tropical regions

Other properties which must be determined and considered before the selection of a particular agent are:

1. The corrosive or other detrimental effects that the agent may have on common materials used in dispensing systems and aircraft.

2. The toxic or irritating effects the use of the agent will have on fire-fighting personnel or other persons in the immediate area of its use.

3. The compatibility of the agent when applied in conjunction with other auxiliary or primary agents used by the services.

The corrosive effects of an agent must be given serious consideration. If an agent causes detrimental effects to its dispensing system after long periods of storage, the system may become unreliable and/or ineffective when the occasion arises for its use. Similarly, an agent which can cause significant corrosion to aircraft components may cause more damage than the fire itself.

Little is known of the corrosiveness of dry chemicals in their normal dry state or when mixed with water. This is one area in which a gap in knowledge is evident.

The corrosiveness of the various halogenated agents and their products of decomposition in a fire is known to be significant over long periods of contact with commonly used materials. However, because of their extremely volatile nature, and the particular applications in which they are used, this is not considered to be a serious problem.

If a large quantity of halon vapors or dissociation products are entrapped in an aircraft compartment, the enclosure can be ventilated, as it will be in any case after significant use of the agent.

Carbon dioxide has no detrimental corrosive effects which may cause a problem.

Water-antifreeze solutions particularly those containing inorganic salts, such as LiCl, will corrode aircraft parts. The aircraft must be washed out well after a fire.

TMB has been claimed to have no effect on commonly used metals, but that it has some effect on elastomers other than GR-I.[14]

The corrosive properties of Met-L-X have not been described in the literature, but one would expect that the sodium chloride content will corrode certain metallic parts of the aircraft.

The toxicity and irritating effects of an agent are also of ' ime importance. Fire-fighting and aircraft personnel will not be capable of working or evacuating efficiently or safely if they are severely irritated or overcome by the agent or its decomposition products.

Commercially available dry chemicals are known to be of relatively low toxicity. Some momentary difficulty in breathing and eye irritation may be experienced, but only if the person is enveloped in a cloud of agent.

The toxicity of halogenated agents has been thoroughly studied[9,21]. Proper precautions must be taken with their use. A recent accident involving halon 2402 has shown a possible serious cardiac effect after short-term exposure. Halon 1301 can be tolerated at concentrations of up to 10% for short periods of time while the limit on halon 1211 is 4 to 5%. CB has anesthetic properties and is toxic to humans at lower levels. Fortunately, the products of decomposition of halogenated hydrocarbons are easily recognizable by the human olefactory system long before their toxic limit is reached.

The major precaution that must be taken with carbon dioxide is that personnel should not be exposed to concentration levels of 9% or more. A 9% concentration can cause instantaneous loss of consciousness in most people.[9]

No extended physiological studies have been conducted to verify the safety of exposure to the decomposition products of TMB. We do not believe that these products will pose a serious problem particularly since TMB is usually used in the open. Similarly, Met-L-X, which is primarily composed of sodium chloride, is not expected to produce any serious effects.

Water-antifreeze solutions are not expected to produce any serious effects except if the solution contacts the eyes or if it is ingested.

The compatibility of an auxiliary agent with foam is another area which must be given consideration. In the interest of the quick extinguishment and securing of an area, it is self-defeating for one agent to substantially reduce the effectiveness of another being used in the immediate vicinity. Ideally, an auxiliary agent should have no effect upon other auxiliary or primary agents.

The compatibility between all the commercially available dry chemicals and the various types of foams used by the military has been the subject of a number of studies[5,22,23]. Both UL and the military require dry chemicals to satisfy certain tests before an agent can be certified as being compatible with foam. It is noted that several of these agents are available in both regular and foam compatible forms. Both have an equal fire-fighting effectiveness but differ in cost with the foam compatible agents being more expensive.

Except for Ansul X for which information is not yet available, each dry chemical has demonstrated an acceptable degree of compatibility with AFFF foam, and all but Purple K have shown compatibility with protein foams.

No compatibility complications are expected between the foams and the gaseous halons and CO_2. These agents are primarily used on fires which are not accessible for foam.

The foam compatibility of CB and possibly halon 1211, which is a liquid at temperatures lower than 25°F, must be determined in large scale fire tests, as must the compatibility of the Halon Foam developed by ADL.

The effect of water spray on foams has been studied[5] to determine the effects of rain on a foam blanket. This should present no problems for aircraft ground fires because water (with antifreeze), if used, will be limited to interior fires in class A combustibles only.

The compatibility of one auxiliary agent with another has not been studied, but it is not considered important. First, it is doubtful that more than one auxiliary agent will be used at the same fire, and there is no scientific basis for suspecting that the effectiveness of one might be decreased when another is used.

Table 3.4 identifies the gaps in knowledge on agent capabilities which exist, while Table 3.5 summarizes the known capabilities of auxiliary agents.

3.7 ENVIRONMENTAL CAPABILITIES AND REQUIREMENTS OF AUXILIARY SYSTEMS

The capabilities of a dispensing system under adverse conditions is as important as the capabilities of the agent being used. As mentioned earlier, Underwriters' Laboratories and the military require extinguishing systems to satisfy a number of tests before they are approved for use.

The UL tests required for dry chemical systems include[14]:

1. Operation Test: not less than 80 percent (by weight) of the agent shall be discharged when the unit is at an angle of 45° from the normal operation position.

TABLE 3.4

KNOWN ENVIRONMENTAL AND PHYSICAL CAPABILITIES OF AUXILIARY AGENTS

	Storage + 140°F (UL)	Storage + 160°F (MIL)	Storage - 80°F (MIL)	Up to 80% humidity (UL)	Up to 100% humidity (MIL)	Dielectric Withstand (UL)	Fungus Growth (MIL)
Potassium Bicarbonate (Purple K)	S	S	S	S	?	S	?
Potassium Chloride (Super K)	S	S	S	S	?	S	?
Sodium Bicarbonate	S	S	S	S	?	S	?
Monoammonium Phosphate (MAP)	S	S	S	S	?	S	?
Monnex (ICI)	S	S	S	S	?	S	?
Ansul X (Ansul Co.)	?	?	?	?	?	?	?
Bromochloromethane (halon 1011, CB)	S	S	S	U	U	N.A.	S
Chlorobromodifluoromethane (halon 1211)	S	S	S	S	S	N.A.	S
Chlorobromodifluoromethane (halon 2402)	S	S	S	S	S	N.A.	S
Bromotrifluoromethane (halon 1301)	S	S	S	S	S	N.A.	S
Carbon Dioxide	S	S	S	S	S	N.A.	S
Halon Foam (ADL)	S	S	S	S	S	N.A.	S
Met-L-X	APPROVED FOR -40°F to + 120°F		?	?	?	N.A.	?
Trimethoxyboroxine (TMB)	S	S	S	U	U	N.A.	?

LEGEND

? = Unknown data

N.A. = Not applicable

S = Data available indicates satisfactory performance

U = Available data indicates unsatisfactory performance

TABLE 3.5

SUMMARY OF KNOWN INFORMATION ON VARIOUS AUXILIARY AGENTS

Legend: 0 = unsatisfactory, 1 = acceptable, 2 = excellent
? = unknown

	Extinguishing Capability of Fire Types				Securing Capability	Compatibility with Protein Foam	Compatibility with AFFF	General Corrosiveness	Toxicity of Agent or Decomposition Products	Cleanliness
	A	B	C	D						
Potassium bicarbonate (Purple K)	0	1	1	0	0	0	1	1	2	0
Potassium chloride (Super K)	0	1	1	0	0	1	1	1	2	0
Sodium bicarbonate	0	1	1	0	0	1	1	1	2	0
Monoammonium phosphate (MAP)	1	1	1	0	0	1	1	1	2	0
Monnex (ICI)	0	2	1	0	1	1	1	2	2	0
Ansul X (Ansul Co.)	0	2	1	0	?	1	1	?	2	0
Bromochloromethane (CB or halon 1011)	1	1	1	0	?	?	?	0	0	1
Chlorobromodifluoromethane (halon 1211)	1	1	1	0	?	?	?	0	1	2
Tetrafluorodibromomethane (halon 2402)	1	1	1	0	?	?	?	0	0	1
Bromotrifluoromethane (halon 1301)	0	1	1	0	0	1	1	0	1	2
Carbon dioxide	0	1	1	0	0	1	1	2	1	2
Halon Foam (ADL)	1	2	1	0	1	?	?	0	1	1
Met-L-X	0	0	0	1	1	?	?	0	2	0
Trimethoxyboroxine (TMB)	0	0	0	1	1	?	?	0	0	1

2. Discharge Range Test: at 70°F, an extinguisher of over 5 lb capacity will discharge practically all its chemical at least 10 feet from the nozzle.

3. Discharge Duration Test: at 70°F, an extinguisher must have an effective discharge time of at least 8 seconds.

4. Operating Temperature Limits Test: from -40°F to 150°F, not less than 85 percent (by weight) of the agent must be discharged.

5. Rain Test: units must operate with no change in performance after exposure to 96 hours of continuous water spray, 72 hours at a temperature of 150°F, and 24 hours at room temperature.

6. Pressure-Retention Test: at 70°F, cartridge-operated units must retain a pressure of at least 50 psi for 15 minutes after the chamber is pressurized.

7. 30-Day Elevated Temperature Test: after 30 days exposure to a temperature of 120°F, a unit must discharge 85 percent (by weight) of its agent charge.

8. Packed Hose Test: units with discharge valves at the end of the hose must start to discharge within 5 seconds when their hoses have been previously packed with agent.

9. Packed Chamber Test: the chamber of the unit is completely filled with agent and conditioned at 150°F. The pressure developed in a cartridge-operated unit must not exceed the factory test pressure.

10. Temperature Cycling Test: after 24 hours at -40°F, 24 hours at 120°F, 24 more hours at -40°F, and 24 hours at 70°F, a unit must discharge at least 80 percent of its agent charge.

11. Rate of Flow Test: at 70°F, the rate of flow from a unit must not vary more than 10 percent from the average of three consecutive tests.

12. Intermittent Discharge Test: no more than one second must elapse from the time the discharge valve of a unit is opened until the agent starts to discharge when a unit is intermittently turned on and off in 2 seconds, or in the case of wheeled units, 5 second cycles.

13. Vibration Test: units must be capable of withstanding a variable frequency test in which frequencies from 10 cps to 60 cps in intervals of 2 cps are used for 5 minutes each. The unit must also withstand 2 hours at the frequency which produced the maximum resonance.

14. Roadability and Rough Usage Tests: wheeled units must withstand towing for 5 miles at 5-7 mph over a variety of surfaces, being dropped three times from a 12 in. platform, and allowing one wheel to strike a wall at 5 mph. Other units must withstand a number of drop tests.

15. Hydrostatic Test: depending on the type of unit, extinguisher shells must withstand 5-6 times the operating pressure.

16. Salt-Spray Corrosion Test: a unit must not be affected by 240 hours exposure to a salt spray (20% salt solution).

17. One-Year Time Leakage Test: stored pressure units must retain their pressure for one year at room temperature, and cartridges must retain their pressure for one year at both room temperatures and 120°F.

A variety of other requirements must also be fulfilled such as markings, abrasion tests of nameplates, etc.

Military specifications for ground support equipment are generally comparable with all of these tests except for the limits of the high- and low-temperature, humidity and fungus growth tests. Other minor differences do exist in test duration times and operating temperatures. For example, the upper operating temperature required by UL of most agents is + 120°F, while the upper temperature for the military is 125°F. It is reasonable to assume that any hardware which will satisfy the UL requirements will also satisfy the military requirement in this case.

Underwriters' Laboratories, as noted previously, require that units be operational from -40°F to +120°F, and have specially rated some manufacturers' units for use at -65°F. The military low-temperature test requires that equipment be stored at -80°F for 72 hours, and then be maintained at -40°F for 24 hours before being discharged. This prolonged storage at -80°F may produce significant effects which are not evident at -40°F or -65°F on elastomeric seals and gaskets. Thus, this is one area where additional testing was required.

The high-temperature test for the military requires equipment to be subjected to 160°F for 48 hours, then brought down to room temperature and operated. UL does not require a similar test.

UL requires agents but not hardware to undergo 80 percent relative humidity tests. Military specifications specify exposure to at least 85 percent relative humidity with temperature cycling for 240 hours. It is noted that both UL and the military require rain and salt spray tests in any case.

Systems for military use in tropical regions must also satisfy fungus resistance tests which are not required by UL.

Thus, it can be concluded that once a piece of hardware had satisfied UL requirements, it will generally satisfy military specifications if it passes the few additional tests required.

4. EXPERIMENTAL PROGRAM

In the previous section, we identified several areas where knowledge relating to the performance of agents and systems under various environmental and fire conditions which are important to the military was lacking. Here we describe the tests that were conducted to fill these knowledge gaps and the results of these tests.

4.1 FIRE TESTS

As indicated earlier, standard fire tests employed by civilian approval laboratories and military agencies are not designed to test the capability of an agent/system for a specific requirement such as aircraft ground fires. Some standard fires (liquid fuel pan fires) are too simple to extinguish by many agents so that differences in effectiveness between these agents are statistically insignificant. It is difficult to use the results of such tests to identify the most effective agents. Other fire tests such as those involving wood cribs and cotton waste are not representative of real-life fuel types and orientations so that the results of extinguishment tests with these fuels may not be adequate for predicting the agent performance in extinguishing typical aircraft ground fires. Two fire tests depicting typical aircraft ground fires were designed and used to compare the effectiveness of various agents. These tests simulated an engine fire with a continuous fuel (JP-4) leak and a fuel spill fire on an inclined plane. Preliminary tests were also conducted on a third type of fire which was believed to present particular fire fighting problems. This fire involved reticulated urethane foam which is commonly used in military aircraft to reduce the explosion hazard in the vapor space of fuel tanks and to slow down spilling rates when the tank is punctured.

4.1.1 Fuel Spill Fire

One fire condition common to many aircraft accidents is the flow and ignition of fuel from a ruptured tank down the incline of the wings or on the ground. To simulate this condition, an apparatus was constructed

of steel plate consisting of a 5 ft long by 3 ft wide incline down which JP-4 fuel was discharged from a manifold at a flow-rate of approximately 10.3 lb/min. Fuel which did not burn on the incline was collected in a 6 ft long by 3 ft wide by 4 in. deep pan containing a 1 in. bed of sand. A schematic drawing of the apparatus is presented in Figure 4.1.

This mockup was in effect a scaled down version of one used by FAA[5] with minor modifications. The first modification concerned the materials of construction. The FAA test was constructed of clay soil and earthen dikes whereas this apparatus was constructed of metal plate which when heated presented a source for fuel reignition. The other major difference involved the design of the incline itself. In the FAA test, the incline was in effect an inclined trough. In this layout, the sides of the incline were open and fuel could flow off the sides of the plate and burn on the concrete ground underneath it. Thus, a more difficult fire was produced.

At the start of each test, the flowing fuel was ignited and the flames allowed to spread completely over the plate and pan. After 1 minute preburn, the fire was extinguished and the time for extinguishment and weight of agent used recorded.

The results of these tests are summarized in Table 4.1. The results indicate that Monnex (ICI), Anxul X, and Potassium Bicarbonate (Purple K) are the most effective and reliable agents in extinguishing this type of fire, in that order.

4.1.2 Engine Fire Simulation

Engine fires are prevalent in many aircraft accidents. To simulate a jet engine fire, a scaled-down version of the test used by FAA[5] was employed. This mockup consisted of a 55-gal steel drum mounted horizontally with its top and bottom removed and in which two 5-gal steel drums, also with tops and bottoms removed, were concentrically supported. A manifold positioned inside the 55-gal drum sprayed JP-4 fuel at a flow-rate of approximately 9.6 lb/min over the interior drums and out of three 1/2 in. diameter holes drilled in the bottom of the large drum, into a

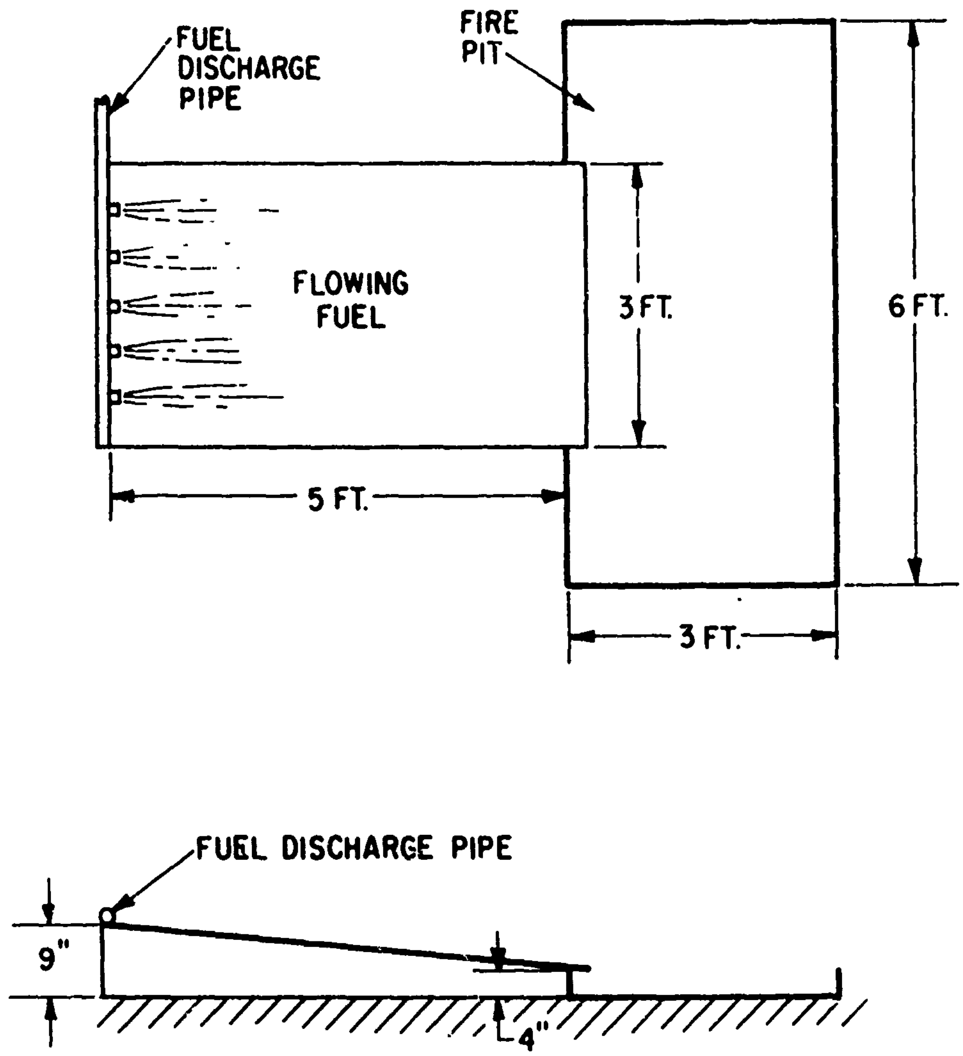


FIGURE 4.1 - SCHEMATIC DRAWING OF THE FLOWING FUEL FIRE TEST

TABLE 4.1

COMPARATIVE FIRE TESTS ON INCLINED PLANE

Agent	Time to Extinguish (sec)	Weight of Agent (lb)	Rate (lb/sec)	Comments
Potassium bicarbonate (PKP)	12.9	13.6	1.06	Fire not fully developed. Poor technique.
	4.5	4.1	.92	Easily extinguished.
	N.E.*	27.3	--	Very poor technique.
	6.3	8.8	1.39	Easily extinguished
Sodium bicarbonate	N.E.	31.4	--	Poor technique
	19	29.8	1.56	Back edge of plate kept reigniting.
	6.5	14.8	2.27	Easily extinguished
Monoammonium phosphate (MAP)	N.E.	24.9	--	Reignition and flashback
	N.E.	25.6	--	Reignition and flashback
Potassium chloride (Super K)	N.E.	18.7	--	Reignitions from back edge of plate
	6.3	13.3	2.11	Easily extinguished
	N.E.	18.1	--	Strong wind, splashed fuel
Monnex (ICI)	2.7	4.3	1.63	Extremely effective
	5.4	2.4	.44	Same extinguisher as in last test, still very effective.
	2.0	2.4	1.20	Extremely effective
Halon Foam (ADL)	N.E.	18.3	--	Controlled well, but ran out before extinguishment
	18.1	18.4	1.01	Some reignitions
CO_2	N.E.	14.1	--	Not effective at all
Ansul X	3.7	6.9	1.86	Very effective
	6.1	8.3	1.36	Same extinguisher as in last test, still very effective
Bromochloromethane (CB)	N.E.	31.3	--	Not very effective, used in spray and stream form.
Bromochlorodifluoromethane (Halon 1211)	N.E.	24.0	--	Not effective, used in spray and stream form.

*N.E. = not extinguished.

6 ft long by 3 ft wide pan containing a 1 in. bed of sand. The bottom of the large drum was supported on legs (30-3/4 inches) above the sand level. A schematic diagram of the engine mockup is given in Figure 4.2.

In each test, the fuel pump was turned on and the fuel ignited. The fuel sprayed over the interior drums, splashed against the supporting struts, and resulted in a pan fire underneath the entire burning configuration. This presented a formidable fire situation which was capable of clearly identifying the most effective agents for this type of fire. After one-minute preburn, the fire was extinguished and the time for extinguishment and weight of agent used as well as other pertinent observations were recorded. The results are shown in Table 4.2.

The results show that Monnex and Ansul X are again the most reliable and effective extinguishants for this application. Potassium chloride (Super K) was unreliable in performance although quite effective when it did extinguish the fire. Potassium bicarbonate (Purple K) did not appear to be effective on this configuration.

4.1.3 Reticulated Foam Tests

In some aircraft crashes, the critical or subsequent impacts of the aircraft with the ground or other obstacles in its crash path are of sufficient force to rupture one or more of the fuel tanks. Many military aircraft fuel tanks are currently being filled with reticulated polyurethane foam . It has been suggested that this combustible foam may increase the intensity of the fire and present difficulties in extinguishment.

A series of tests was conducted to examine whether or not reticulated foam presents particular problems during the extinguishment of a ruptured tank fire.

The first configuration tested consisted of a 42 inch long by 20-3/4 inch wide by 7-1/2 inch thick pad of foam (Scott Co.) which was placed in a 6 ft long by 3 ft wide by 4 inch deep metal pan. A manifold was placed on top of the pad to discharge JP-4 at 10.3 lb/min. A schematic diagram of the apparatus is given in Figure 4.3A.

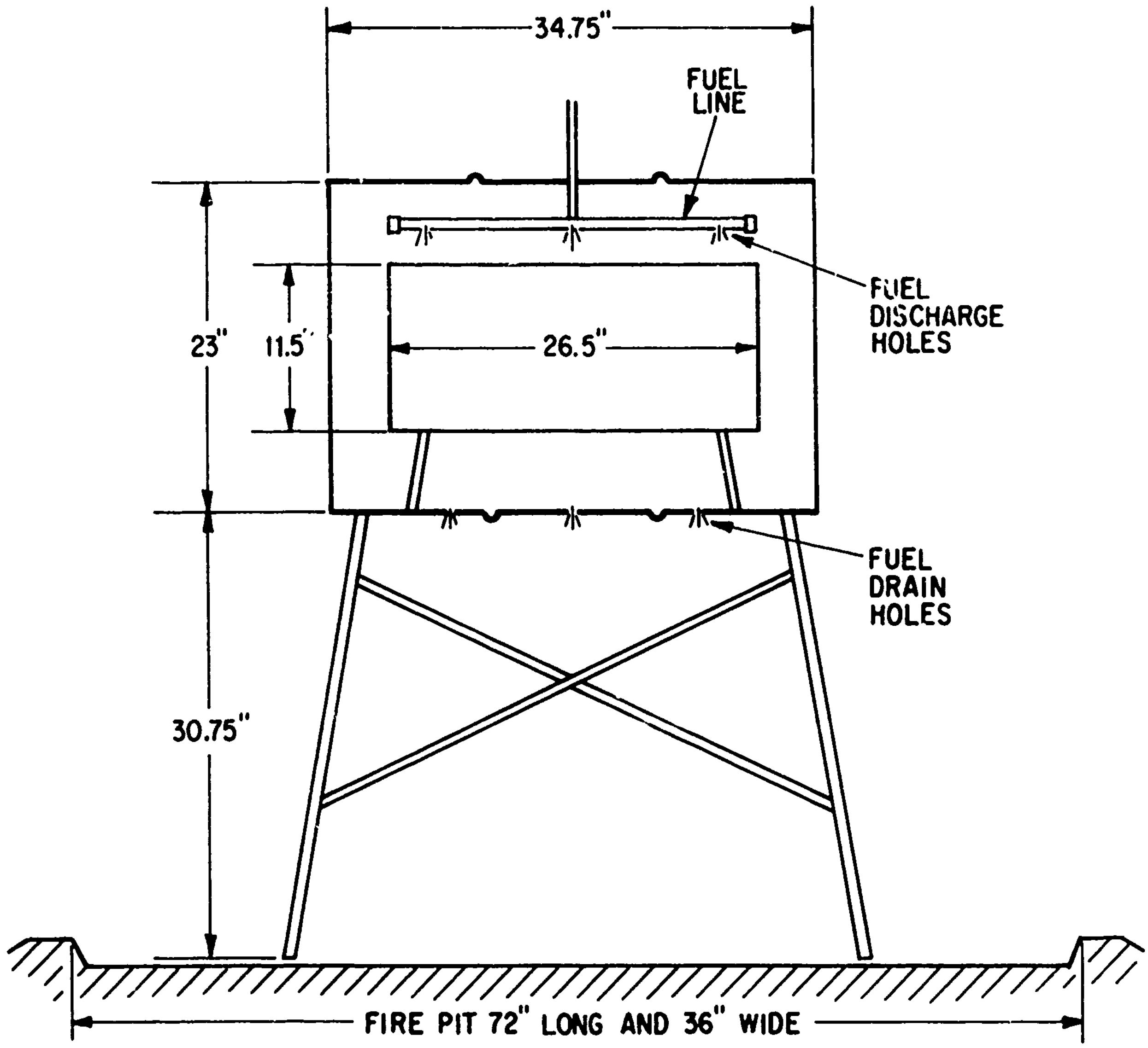


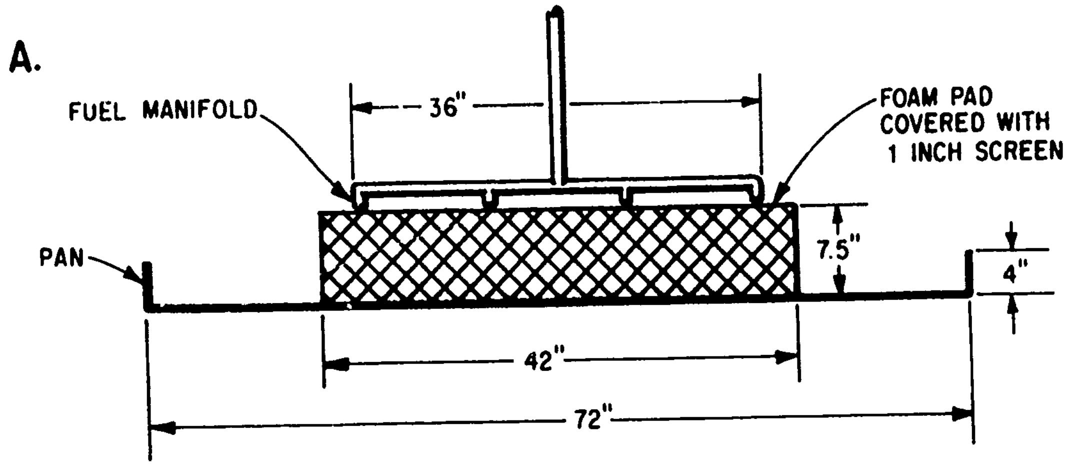
FIGURE 4.2-SCHEMATIC DRAWING OF THE SIMULATED JET ENGINE MOCKUP.

TABLE 4.2

COMPARATIVE FIRE TESTS ON A SIMULATED AIRCRAFT ENGINE

	Time to Extinguish (sec)	Weight of Agent (lb)	Rate (lb/sec)	Comments
Potassium Bicarbonate (PKP)	N.E.*	27.6	--	Poor technique
	23.4	25.9	1.11	Barely put out in time
	N.E.	27.5	--	Continued to reignite
Sodium Bicarbonate	N.E.	34.3	--	Continued to reignite
Potassium Chloride (Super K)	N.E.	18.9	--	Continued to reignite
	N.E.	26.3	--	Continued to reignite
	4.4	9.5	2.16	Very effective
	6.0	7.3	1.21	Same extinguisher as in last test, still effective.
Monnex (ICI)	3.5	4.8	1.36	Very effective
	7.0	7.8	1.11	Same extinguisher as in last test, still effective.
	8.5	11.9	1.40	Very effective, same extinguisher used for third time.
Halon 1211	N.E.	16.5	--	Not effective, used in spray form.
	N.E.	24.2	--	Not effective, used in stream form.
Ansul X	5.5	6.2	1.13	Very effective
	9.5	10.9	1.15	Same extinguisher as above, still effective.
Halon Foam (ADL)	N.E.	20.8	--	Continued to reignite
Bromochloromethane (CB)	N.E.	31.4	--	Not effective, used in spray and stream form.

*N.E. = not extinguished.



PAN IS 36" WIDE
FOAM PAD IS 20.75" WIDE

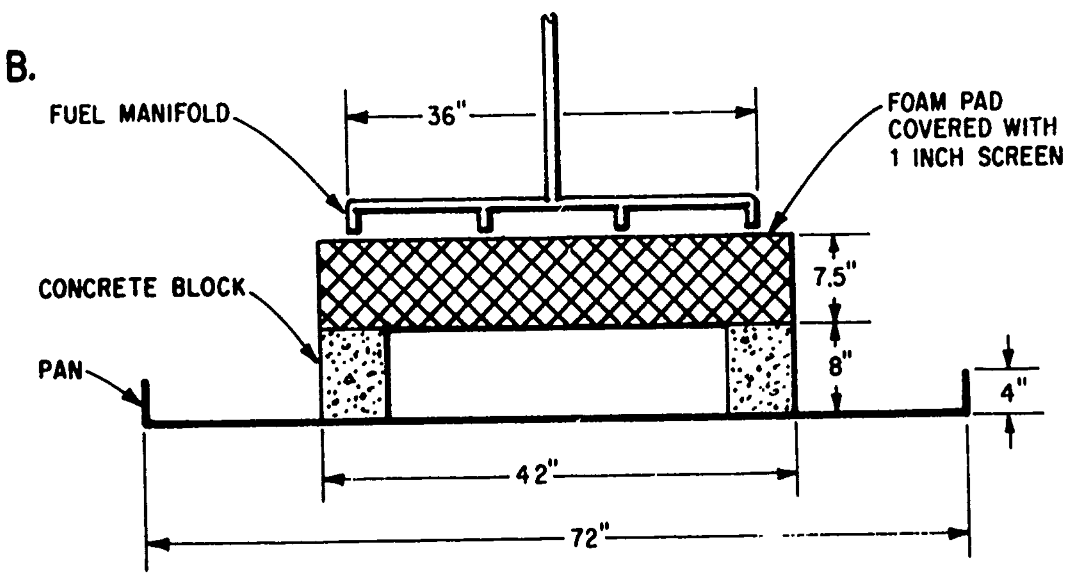


FIGURE 4.3 - RETICULATED FOAM TEST FIRES

Before the test, approximately 10 lb of fuel was spread evenly over the top of the pad. Then the fuel flow was started, and the top of pad ignited. After a 30 second preburn, which was sufficient to start the entire pan and the sides and top of the foam pad burning, potassium bicarbonate (Purple K) was used in a 30-pound portable extinguisher to extinguish the fire. The extreme ease and quickness of extinguishment (5.2 seconds using 6.7 lb) led to the conclusion that the foam had not significantly contributed to the severity of the fire condition, and that this was no more difficult to extinguish than a small pan fire.

The next configuration tried consisted of a similar pad suspended over the pan by two 16-inch high concrete blocks on end. To hold down the pad from the force of the extinguisher, a cage was built of 1 inch wire screen which fit over the pad. As before, JP-4 was discharged from a manifold resting on top of the pad at 10.3 lb/min. A schematic diagram of the configuration is given in Figure 4.3B. The fuel was allowed to soak the pad for 30 seconds after which it was ignited and allowed to burn for 30 seconds. Purple K was then used but it was unsuccessful in extinguishing the fire. The difficulty arose from the fact that the fire began burrowing under the pad, causing several large hemispherical burning cavities which kept reigniting the pan fire and eventually the top of the pad. To extinguish the pad, it was necessary to turn off the fuel flow and turn the pad over, at which time a back-up Purple K extinguisher quickly extinguished the fire. It was interesting to note that during the soaking period, the pad did not appear to absorb much of the fuel from the manifold but allowed it to flow right through to the pan below.

This test was repeated on a less windy day with minor modifications to the configuration and procedure. The pad was lowered by 8 inches and 10 lb of fuel was spread over the pad before ignition. The results with Purple K were essentially the same.

Bromochloromethane (CB) was used in another test with the same configuration. It was hoped that the liquid directed to the top of the pad would penetrate the pad and extinguish the fire under the pad. As

with the Purple K, the pan fire and fire on the top and sides of the foam could easily be extinguished but the burrowing fire problem remained.

Finally, Monnex (ICI), which had shown excellent capabilities in the other simulation tests, was used. The fire was extinguished with 28 lb of agent in 15 seconds. Examination of the foam pad after the test showed that Monnex was capable of extinguishing the burrowing fire quite effectively.

These tests suggest that reticulated foam may present some problem in fire extinguishment and thus needs to be considered more carefully in the second phase of this study.

4.2 CORROSIVE EFFECTS OF AGENTS

The objective of this experiment was to determine the corrosive or other detrimental effect that the agents might have or create in contact with aluminum, brass, titanium, steel, and elastomers normally used in dispensing equipment and in aircraft structures.

Aluminum, brass, mild steel, stainless steel, titanium, neoprene rubber and nitrile rubber were subjected to the following tests:

(1) They were immersed in 10 grams of each agent shown in Table 4.3 and stored in glass jars @ 130°F for 20 days; and

(2) The metals only were immersed in a mixture of 5 grams of agent and 5 grams of distilled water and stored in glass jars @ 130°F for 20 days.

The agents, agent slurries, and metals and elastomers were inspected for evidence of corrosive attack and/or deterioration at the conclusion of the test period. The agents tested are shown in Table 4.3.

Table 4.4 shows the results of adding water to the dry chemicals. The results of the dry storage are shown in Table 4.5 and of the wet storage in Table 4.6.

These results show that the agents, in their normal dry state, had little effect on the various metals and elastomers on test, whereas the

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TABLE 4.3

AGENTS FOR CORROSION TESTING

Supplier	Tradename	Treatment	Composition
Ansul	Met-L-X	Stearate & TCP	$NaCl$
ICI	Monnex	Special	$KHCO_3$ + Urea
Ansul	Plus Fifty C	Silicone	$NaHCO_3$
Ansul	Plus Fifty B	Stearate	$NaHCO_3$
Ansul	Foray (MAP)	Silicone	$(NH_4)H_2PO_4$
Safety First	Super K	Silicone	KCl
Ansul	Purple K	Silicone	$KHCO_3$
Callery Chemical Co.	TMB (liquid)	--	$(CH_3O)_3H_3B_3N_3$
Dow	CB (liquid)	--	CH_2ClB

TABLE 4.4

WET MIXTURE MISCIBILITY, 1:1 MIXTURE WITH WATER

Met-L-X	Not miscible, forms two layers, agent floating on water
Monnex	Miscible, forms a sludge
Plus Fifty C	Miscible, forms a thin paste
Plus Fifty B	Miscible, forms a thin paste
MAP	Not miscible, forms two layers, agent floating on water
Super K	Not miscible, forms two layers, agent floating on water
Purple K	Miscible, forms a heavy paste

TABLE 4.5

DRY STORAGE TEST RESULTS

Agents	Aluminum	Brass	Mild Steel	Stainless Steel	Titanium	Neoprene	Nitrile
Met-L-X	No Effect	No Effect	Slight Rust Spotting	No Effect	No Effect	No Effect	No Effect
Monnex	"	"	No Effect	"	"	"	"
Plus Fifty C	"	"	"	"	"	"	"
Plus Fifty B	"	"	"	"	"	"	"
MAP	"	"	"	"	"	"	"
Super K	"	"	"	"	"	"	"
Purple K	"	"	"	"	"	"	"
TMB	"	Hazy Sol. No Effect	White Sediment No Effect	"	"	Dark Brown Solution No Effect	Very dark Green Solution Severe Swelling
CB*	"	No Effect	No Effect	"	"	"	No Effect

*CB liquid evaporated within a few days @ 130°F and left no apparent effect on either the metals or elastomers.

TABLE 4.6

WET MIXTURE TEST RESULTS

Agent Mixtures	Aluminum		Brass		Mild Steel		Stainless Steel		Titanium	
	Liq.	Metal	Liq.	Metal	Liq.	Metal	Liq.	Metal	Liq.	Metal
Met-L-X/Water	N.C.*	Some etching	Discolored around metal	Severe attack	Rusty	Severe attack	Rusty	Mild attack	N.C.	No effect
Monnex/Water	N.C.	No effect	Blue colored solution	Mild attack	N.C.	No effect	N.C.	No effect	N.C.	No effect
Plus Fifty C/ Water	N.C.	No effect	N.C.	Mild attack	N.C.	No effect	N.C.	No effect	N.C.	No effect
Plus Fiffy B/ Water	N.C.	No effect	N.C.	Moderate attack	N.C.	No effect	N.C.	No effect	N.C.	No effect
MAP/Water	N.C.	Moderate attack	N.C.	Severe attack	N.C.	Severe attack	N.C.	No effect	N.C.	No effect
Super K/Water	N.C.	Moderate attack	N.C.	Severe attack	Rusty	Severe attack	N.C.	Slight corroson	N.C.	No effect
Purple K/Water	N.C.	Very slight attack	N.C.	Mild attack	N.C.	No effect	N.C.	No effect	N.C.	No effect

*N.C. = No change

agent/water mixtures caused considerable corrosive attack on certain metals such as aluminum, brass, and mild steel. The attack on the metals was most evident in slurries made by agents not miscible with water.

- Titanium was not affected by any of the agent mixtures,
- Stainless steel suffered only slight attack by Super K and Met-L-X slurries.
- Aluminum was not attacked by Monnex, Plus Fifty B and C, and only slightly attacked by Met-L-X and Purple K slurries. It was moderately attacked by MAP and Super K slurries.
- Brass was attacked by all agent mixtures, but to a lesser degree by Purple K, Monnex, and Plus Fifty C slurries.
- Mild steel was not attacked by Purple K, Plus Fifty B and C, and Monnex, but severely attacked by Met-L-X, MAP and Super K slurries.

4.3 ENVIRONMENTAL TESTS

4.3.1 Low Temperature Storage and Discharge

The objective of this experiment was to determine the low-temperature environmental effect on storage and discharge of dry chemical agents and extinguisher dispensing systems.

Specification Mil-E-4970A, Paragraph 4.2.2, Procedure II was followed. One stored pressure and one cartridge-pressurized dry chemical extinguishers filled with Super K and Purple K, respectively, were stored for 72 hours at -80°F. The extinguishers were visually inspected and then maintained at -40°F for an additional 24 hours. At the conclusion of the exposure period, and while at -40°F, the equipment was operated. The equipment temperature was raised to room conditions and again visually examined.

The stored pressure extinguisher filled with Super K and initially pressurized to 350 psig lost its pressure after 24 hours storage at -80°F and was taken off the test. The extinguisher was later repressurized at room temperature and it maintained its pressure.

The cartridge pressurized Purple K extinguisher successfully passed the -80°F storage test and operated normally after storage at -40°F, and after being brought to room temperature. This test suggests that stored pressure extinguishing systems may lose their pressure if exposed to low temperatures for prolonged periods of time and thus are unreliable. Cartridge pressurized extinguishers would be more reliable under these conditions.

4.3.2 High-temperature Storage

The objective of this experiment was to determine the high-temperature environmental effect on storage and discharge of dry chemical agents and extinguisher dispensing systems.

Specification Mil-E-4970A, Paragraph 4.1.2, Procedure II was followed. One stored pressure and one cartridge pressurized dry chemical extinguishers filled with Super K and Purple K, respectively, and one large and one small stored pressure Halon Foam (ADL) extinguishers, were stored at 160°F for 48 hours. Visual inspection was conducted and storage pressures noted. The temperature was then reduced to prevailing room conditions and the extinguisher pressures noted. The extinguishers were discharged upon reaching room temperature.

The increase in pressure of the three stored pressure extinguishers during the test period is shown in Table 4.7. The Halon Foam extinguishers' pressure increased roughly by 125-130%. The pressure in the nitrogen-pressurized, dry-chemical (Super K) extinguisher, initially pressurized to 350 psi increased by about 20%.

Following a cool-down period of about 20 hours, the three stored pressure extinguishers had returned to their initial charging pressures and all extinguishers including the cartridge pressurized Purple K extinguisher performed normally.

TABLE 4.7

EFFECT OF HIGH TEMPERATURES ON STORED PRESSURE EXTINGUISHERS

Time @ 160°F (hrs.)	Small Halon Foam (Quart Size)	Large Halon Foam (2 Gallon Size)	Super K 30-lb
0 (initial reading)	165	180	350
1/2	270	250	380
1 - 1/2	330	290	410
3	380	350	425
24	370	400	425
48 (removed from oven)	370	400	425
20 (cooled @ RT)	165	180	350

4.3.3 Humid Storage

The objective of this test was to determine the effect of humid storage conditions on dry chemical agents and extinguisher dispensing systems.

Specification MIL-E-4970A, Paragraph 4.3.1, Procedure I was followed. A cartridge pressurized dry chemical extinguisher filled with Purple K was subjected to 10 cycles of eight hours at 160°F and 95% relative humidity and 16 hours at 100°F and 95% relative humidity for a total of 240 hours. Following completion of the test period, the extinguisher was brought to prevailing room conditions, inspected, and discharged.

In addition, another test was conducted in which about 30 grams of each dry chemical agent was stored at 100°F and 95% relative humidity in open 2-oz. glass jars for a period of 7 days. The agents were inspected for packing and/or caking following the exposure period.

The cartridge-pressurized, dry-chemical extinguisher showed no evidence of rusting or deterioration following the 10-cycle humidity test. The extinguisher functioned normally immediately after completing the 240 hour test period.

The samples of dry chemical agents exposed to 100°F and 95% relative humidity for seven days showed varying resistance to packing and caking. The results shown in Table 4.8, indicate that, except for Monnex, the agents miscible with water showed some degree of caking, while those agents not miscible with water (see Table 4.4) and Monnex showed no appreciable change. Sodium bicarbonate with silicone treatment had a densely caked, 1/32" thick surface layer with the remainder of the powder caked throughout with a clay or putty-like consistency. Sodium bicarbonate with a stearate treatment had a 1/4" to 1/8" thick caked layer, but the agent beneath was free flowing. Purple K showed a slight degree of thickening throughout the agent but remained fairly free to flow.

TABLE 4.8

RESULTS OF DRY CHEMICAL AGENT EXPOSURE TO 100% HUMIDITY

Agent	Miscibility With Water	Humidity Exposure
Met-L-X (Ansul)	No	No appreciable effect
Monnex (ICI)	Yes	No appreciable effect
Sodium Bicarbonate (silicone treatment)	Yes	Surface layer about 1/32" thick reacted with moisture and formed a dense blue colored caked layer, remainder of powder is caked throughout with a clay or putty-like consistency.
Sodium Bicarbonate (stearate treatment)	Yes	Surface layer about 1/4" to 3/8" caked, but remainder of agent beneath is free flowing.
Monoemmonium Phosphate (silicone treatment)	No	No appreciable effect
Potassium Chloride-silicone treatment (Super K)	No	No appreciable effect
Potassium Bicarbonate-silicone treatment (Purple K)	Yes	Slight caking or thickening throughout, still relatively fluid.

4.3.4 Fungus Growth Test

The objective of this test was to determine the environmental effect of fungus growth as encountered in humid tropical regions on exposed chemical agents and extinguisher delivery systems.

Specification Mil-E-4970A, Paragraph 4.7.1 was followed. Spore suspensions of four groups of fungi as specified in the military specification were sprayed on the surfaces of 10 gram samples of each chemical agent in petri dishes, on the handle and valve mechanism of a cartridge-pressurized dry chemical extinguisher, and on cut samples of reinforced neoprene hose. The inoculated samples were stored at 86°F and 95% relative humidity for a period of 28 days. At the end of the test period, the materials were inspected for evidence of fungus growth.

There was no evidence of supportive growth on any of the dry agents. The CB liquid evaporated during the test period and the TMB liquid solidified, but neither showed evidence of fungus growth.

The extinguisher and its fittings showed no evidence of supportive fungus growth. Small isolated spots of fungus growth were noted on the fungus spore solution. A three inch section of the same hose hung on the extinguisher showed no evidence of interior or exterior fungus growth.

5. SELECTION OF AGENTS AND SYSTEMS

5.1 RATIONALE FOR THE SELECTION

To select candidate agents and systems for aircraft ground fire suppression, the following factors were considered:

- The locations where aircraft ground fires could occur
- The types, quantities and distribution of fuels that may be involved
- The capabilities of commercially available agents and systems

The location of the fire determines its accessibility to fire-fighting personnel which, in turn, determines the desirable range of throw of the auxiliary extinguishing hardware to be used. The type of fuel involved in a fire determines the choice of suitable and effective extinguishing agent, whereas the quantity and distribution of the fuel dictates additional requirements on the size of hardware that can dispense this agent. The rationale for selection is displayed graphically in Figure 5.1.

5.2 SELECTION OF AUXILIARY AGENTS

To compare all of the agents considered, while taking all factors into account, a numerical rating scheme was devised.

In Table 5.1 a tabulation is presented showing the extent to which each of the agents identified in Section 3.2 possesses the characteristics of ideal auxiliary agents identified in Section 2.3. Table 5.2 presents a tabulation showing the extent to which each of the characteristics of ideal auxiliary agents is important in combating each of the nine fire types identified in Chapter 2.

The numerical ratings given in both of these tables were correlated and summed to provide an overall indication of the relative capabilities and desirable characteristics of the auxiliary agents considered.

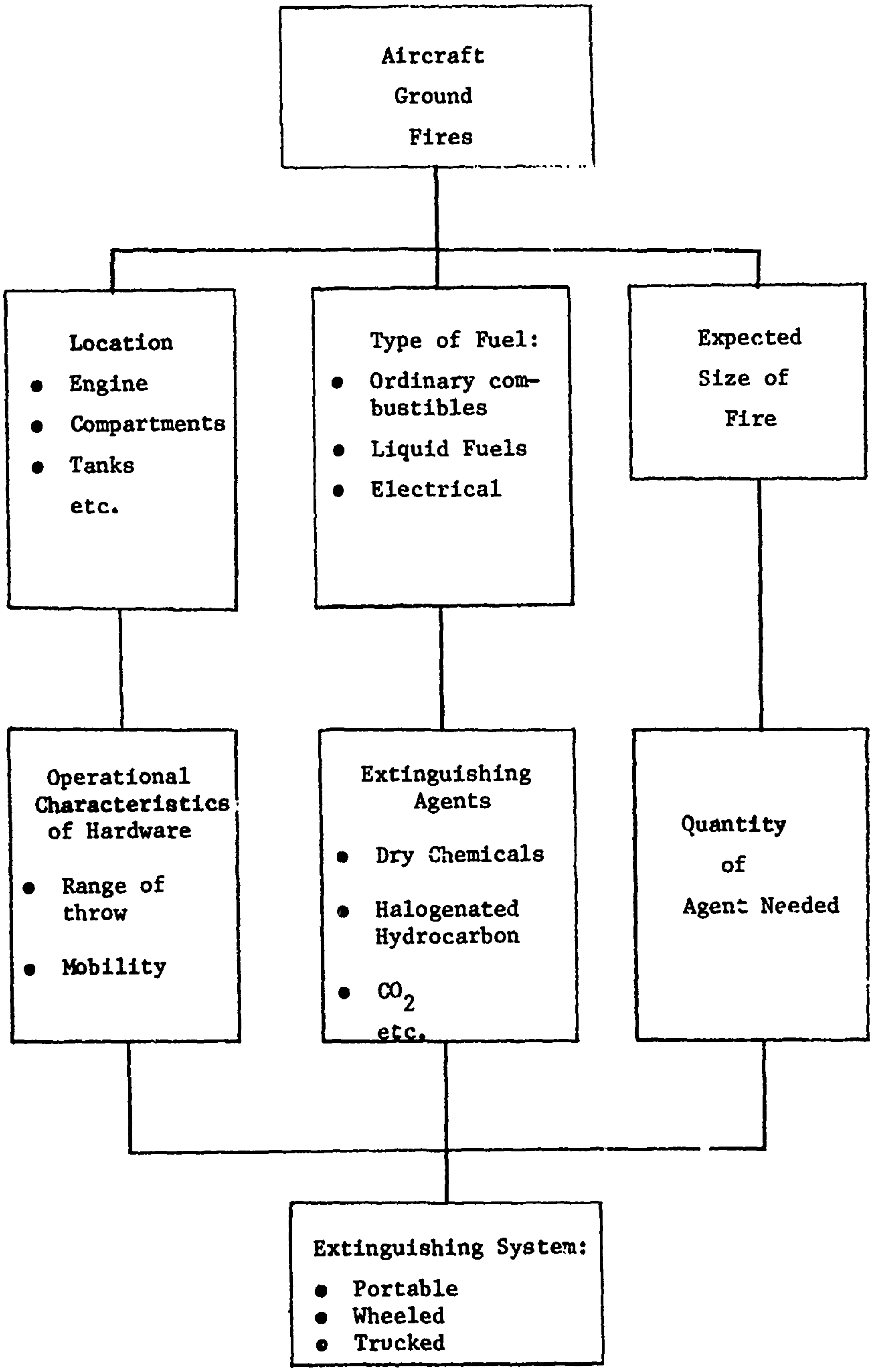

Figure 5.1 Rationale for the Selection of Agents and Systems

TABLE 5-1

PROPERTIES OF EVALUATED AUXILIARY AGENTS

	Quick knockdown, early fire suppression, prolonged securing	Capable of extinguishing more than one kind of fuel fire	Compatible with foams	Prolonged storage under environmental extremes	Minimum corrosive effects	Non-toxic and non-irritating	Cost-effective	Clean	No increase in visibility problems
Potassium bicarbonate (Purple K)	1	1	1	2	1	1	1	0	1
Potassium chloride (Super K)	1	1	2	2	0	1	1	0	1
Sodium bicarbonate	1	1	2	2	1	1	1	0	1
Monoammonium phosphate (MAP)	1	1	2	2	0	1	1	0	1
Monnex (ICI)	2	2	2	2	2	1	1	0	1
Ansul X (Ansul Co.)	2	2	1(?)	2	1(?)	1	2	0	1
Bromochloromethane (CB or halon 1011)	1	2	2	2	1	0	1	1	1
Chlorobromodifluoromethane (halon 1211)	1	2	2	2	2	1	1	2	1
Tetrafluorodibromomethane (halon 2402)	1	2	2	2	1	0	0	1	1
Bromotrifluoromethane (halon 1301)	1	1	2	2	2	1	0	2	1
Carbon dioxide	0	1	2	2	2	1	0	2	1
Halon Foam (ADL)	1	2	2	2	2	1	0	1	1
Met-L-X	0	0	1(?)	2	0	1	1	0	1
Trimethoxyboroxine (TMB)	0	0	1(?)	2	1	0	0	0	0

Legend
0 = poor
1 = fair
2 = good

TABLE 5.2

THE IMPORTANCE OF IDEAL AUXILIARY AGENT PROPERTIES IN EXTINGUISHING TYPICAL AIRCRAFT GROUND FIRES

Ideal Property of Agent	Two-dimensional Fires	Three-dimensional Fires	Fires in Habitable Compartments	Fires in Nonhabitable Compartments	Electrical Fires	Magnesium Fires	Engine and Nacelle Fires	Hidden Floor Space Fires	Fuel Tank Fires	Engine Stack Fires
Quick knockdown early suppression, prolonged securing	2	2	2	2	2	2	2	2	2	2
Capable of extinguishing more than one kind of fuel fire	1	1	2	2	1	1	1	1	2	0
Compatible with foams	2	1	0	0	0	0	0	0	1	0
Prolonged storage	0	0	0	0	0	0	0	0	0	0
Minimum corrosiveness	0	1	1	1	2	1	2	2	1	2
Non-toxic and non-irritating	1	1	2	1	1	1	1	1	1	1
Cost-effective	1	1	1	1	1	1	1	1	1	1
Clean	0	0	1	0	2	0	2	2	0	2
No increase in visibility problems	1	1	2	1	1	1	1	1	1	1

LEGEND

0 = unimportant

1 = important

2 = very important

This was done by taking the number associated with each agent for each ideal characteristic from Table 5.1, and multiplying it by the corresponding number given in Table 5.2 showing the extent to which each characteristic is important for each fire type. The summation of the values calculated for each fire type are presented in Table 5.3. The summation for all fire types determined the final total achieved by each agent.

Using PKP as an example, for two-dimensional fires, each number in the first row of Table 5.1, (1, 1, 1, 2, 1, 1, 1, 0, 1)is multiplied by its corresponding number in the first column of Table 5.2 (2, 1, 2, 0, 0, 1, 1, 0, 1). The summation of these products (1 x 2 + 1 x 1 + 1 x 2 + 2 x 0 + 1 x 0 + 1 x 1 + 1 x 1 + 0 x 0 + 1 x 1) results in the number 8 which is shown in Table 5.3 for PKP on two-dimensional fires. The repetitionof this calculational procedure for each fire type and the summation for all fire types gives a final total of 84.

Comparison of the results of this procedure clearly indicates that Monnex, Ansul X, and halon 1211 should be further investigated as final candidate agents.

It is realized that the assigning of numerical values to the capabilities and characteristics of the agents involves a fair amount of individual judgement. Nevertheless, the values presented were decided upon as objectively as possible, taking into account all information presently available.

5.3 RECOMMENDED AGENTS AND SYSTEMS

In our review of the locations of aircraft ground fires and the fuels that may be involved, we identified the following areas:

- Engine and nacelle: aircraft fuels and hydraulic oil
- Compartments

  Habitable: small quantities of ordinary combustibles,
  small electrical fires,

TABLE 5.3

RATINGS OF AUXILIARY AGENTS FOR TYPICAL AIRCRAFT GROUND FIRES

Agent	Two-dimensional Fires	Three-dimensional Fires	Interior Fires in Habitable Compartments	Interior Fires in Nonhabitable Compartments	Electrical Fires	Magnesium Fires	Engine and Nacelle Fires	Hidden Floor Space Fires	Fuel Tank Fires	Stack Fires	Total
Potassium bicarbonate (Purple K)	8	8	10	8	8	7	8	8	9	7	81
Potassium chloride (Super K)	10	8	9	7	6	6	6	6	9	5	72
Sodium bicarbonate	10	9	10	8	8	7	8	8	10	7	85
Monoammonium phosphate (MAP)	10	8	9	7	6	6	6	6	9	5	72
Monnex (ICI)	13	13	15	13	13	11	13	13	15	11	130
Ansul X (Ansul Co.)	12	12	15	13	12	11	12	12	14	10	123
Bromochloromethane (CB or halon 1011)	10	9	11	9	10	7	10	10	11	8	95
Chlorobromodifluoromethane (halon 1211)	11	11	15	11	15	9	15	15	13	13	128
Tetrafluorodibromomethane (halon 2402)	9	8	10	8	9	6	9	9	10	7	85
Bromotrifluoromethane (halon 1301)	9	9	12	8	13	7	13	13	10	12	106
Carbon dioxide	7	7	10	6	11	5	11	11	8	10	86
Halon Foam (ADL)	10	10	13	10	12	8	12	12	12	10	109
Met-L-X	5	4	5	3	3	3	3	3	4	3	36
Trimethoxyboroxine (TMB)	2	2	1	1	2	1	2	2	2	2	17

Cargo: medium and large quantities of ordinary combustibles such as cardboard boxes, wood, canvas, tires, and liquid fuels such as JP-4, JP-5, AVGAS and hydraulic oil.

- Electrical Equipment: wiring, potting compounds, plastics, etc.
- Fuel Tanks: running fuel on incline of wing or runway. Also reticulated foam if present in tank and exposed to fire.
- Wheel and Brake Assembly: magnesium, hydraulic oil, tire and possibly aircraft fuel
- Helicopter Engine Stack: fuel vapor
- Hidden Floor Spaces: hydraulic oil

By matching the tested or claimed capabilities of agents to extinguish various fuel fires against the types of fuels that may be involved in aircraft ground fires, we arrived at three agents that appeared to be effective on the largest number of fuels. These agents are: Monnex, Ansul X and halon 1211. This is in agreement with the results of Table 5.3.

For magnesium fires a new effective agent should be developed and tested against TMB and Met-L-X.

An examination of the location and typical sizes of aircraft fires suggests the use of the following auxiliary hardware:

- Engine and nacelle: wheeled and truck mounted
- Compartment:

Small	20-30 lb or 1 to 2 1/2 gal portable
Medium	20-30 lb or 1 to 2 1/2 gal portable
Large	30-lb portable, wheeled or total flooded

- Electrical Fires: 20 to 30-lb or 1 to 2 gal portable
- Fuel Tanks: wheeled, truck mounted
- Magnesium Wheel: 20-30 lb portable
- Stack Fires: 20-30 lb portable
- Floor Space fires: 20 to 30-lb portable, wheeled

Our recommended test program for Phase II combines the candidate agents and hardware described above. The aircraft fire mockups, agents and hardware are shown in Table 5.4. It would be preferable if each test series included at least one agent previously used for the same or similar purposes to provide a basis for comparisons. These tests will provide data to fill gaps in knowledge that could not be filled within the time limitations of Phase I. Where appropriate, we also recommend that some tests be conducted in the presence of foam to examine the compatibility of the auxiliary agents with foam under realistic fire conditions.

We expect that the proposed tests would allow us to reduce the number of agents and systems even further and to provide the optimum requirements for aircraft fire protection without jeopardizing aircraft safety.

TABLE 5.4

SUMMARY OF RECOMMENDED TESTS IN PHASE II

Fire Mockup	Fuel(s)	Extinguishing Agents	Hardware
Engine and Nacelle large and small	JP-4, JP-5 or AVGAS	Monnex, Ansul X, CB, Halon 1211(with primary foams)	30-lb or 2 1/2 gal portable 150 to 300-lb wheeled
Compartment-small, medium, and large Types A and B fuels	Wood, canvas tires, JP-4, JP-5, AVGAS, Hydraulic oil	Monnex, Ansul X, CB, Halon 1211, Water (with antifreeze)	20 to 30-lb or 1 to 2 1/2 gal portable 150 to 300-lb wheeled
Electrical Components	Wiring, potting compounds	CB, Halon 1211, CO_2, Monnex, Ansul X	20 to 30-lb or 1 to 2 1/2 gal portable
Running Fuel on Incline	JP-4, JP-5 AVGAS	Monnex, Ansul X, Halon 1211, CB (with primary foam)	150 to 300-lb wheeled
Magnesium Wheel and Brake Assembly	Magnesium, hydraulic oil, rubber	TMB, Met-L-X, a new agent	20 to 30-lb portable
Reticulated Foam Tank	Reticulated foam; JP-4, JP-5 or AVGAS	Monnex, Ansul X, Halon 1211	30-lb or 2 1/2 gal portable 150-lb wheeled
Helicopter Stack	JP-4	Monnex, Ansul X, Halon 1211, CO_2, CB	20 to 30-lb or 1 to 2 1/2 gal portable
Hidden Oil Leak in Floor	Hydraulic oil	Monnex, Ansul X, CO_2, CB, Halon 1211	20 to 30-lb or 1 to 2 1/2 gal portable

6. CONCLUSIONS AND RECOMMENDATIONS

1. Tests conducted on simulated aircraft engine fires and fires simulating burning fuel running from a ruptured tank showed that two new agents: "Monnex" and "Ansul X" are superior to any other agent currently available on the U.S. market in extinguishing this type of fire.

2. Tests on fires in reticulated foam suggest that these fires may be difficult to handle because of the tendency of the fire to burrow into the foam where it cannot be reached by the extinguishant. Additional tests with these foams are recommended.

3. Stored pressure extinguishers appear to be unreliable at the low temperatures (-80°F) that are required for military storage. Cartridge pressurized extinguishers would be more reliable but their range of throw is nearly half of that of stored pressure extinguishers.

4. Large scale suppression tests recommended for the second phase should include simulations of the following fires:

   Engine and Nacelle
   Compartment (small, medium and large)
   Electrical Equipment
   Running Fuel on Incline
   Magnesium Wheel and Brake Assembly
   Reticulated Foam Tank
   Helicopter Stack
   Hidden Oil Leak in Floor Space

   Halon 1211, Monnex, and Ansul X should be investigated further as final candidate agents. Systems to be used on each fire are provided in Table 5.4.

5. Existing magnesium fire extinguishing agents and systems are unsatisfactory. It is recommended that work be conducted to formulate a more effective magnesium fire extinguishing agent and to develop an appropriate dispensing system for this agent.

6. There is a wide variety of nozzles and delivery valves on portable and wheeled extinguishers particularly those handling dry chemicals. We recommend that an optimization program be conducted to improve nozzle and deliverv mechanism design and to maximize the effectiveness of portable and wheeled dry chemical extinguishers.

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